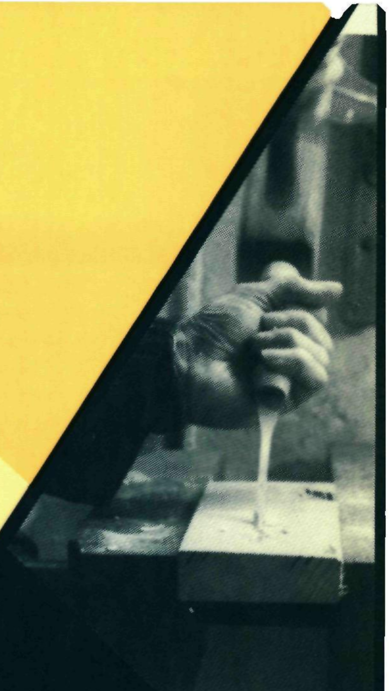
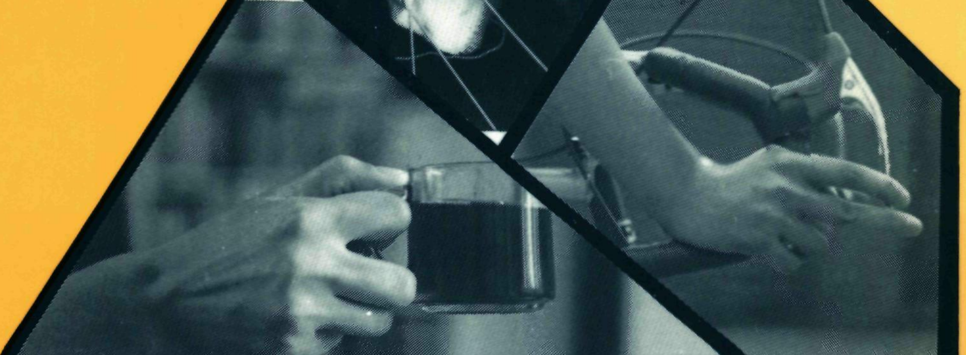
WRIST JOINT KINEMATICS AND LIGAMENT BEHAVIOUR



HANS H.C.M. SAVELBERG



WRIST JOINT KINEMATICS AND LIGAMENT BEHAVIOUR

CIP-GEGEVENS KONINKLIJKE BIBLIOTHEEK, DEN HAAG

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WRIST JOINT KINEMATICS AND LIGAMENT BEHAVIOUR

Een wetenschappelijke proeve op het gebied van de medische wetenschappen

Proefschrift ter verkrijging van de graad van doctor
aan de Katholieke Universiteit Nijmegen, volgens het besluit van het
college van decanen in het openbaar te verdedigen
op woensdag 22 januari 1992 des namiddags te 3.30 uur

door

Hans Hubert Cornelis Marie Savelberg

geboren op 28 februari 1962 te Heerlen

PROMOTORES: PROF. DR. J.M.G. KAUER
PROF. DR. IR. R. HUISKES

STREEF

ONBEKOMMERT

NAAR

HET IDEALE

(uit Loesje, 1986)

Aan pa en ma

CONTENTS

INTRODUCTION

INTRODUCTION

The wrist joint ensures the movability of the hand relative to the forearm. This joint offers the hand two degrees of freedom when moving relative to the forearm. Flexion and deviation movements as well as combinations of these are possible. Movements about a longitudinal axis are excluded by the mechanism of the wrist joint. The mechanical construction, which enables these motions, has many elements, which are interrelated in a complex way. It comprises the radius, eight carpal bones and five metacarpals, a complex of ligaments and the ulnar articular disc. The geometry, material characteristics and the positions of these structures relative to each other are the main factors determining the mechanism of the wrist joint.

It is the aim of this thesis to contribute to the functional morphological understanding of the wrist joint. Biomechanical methods are the tools used in this study to reach this goal.

THEORETICAL BACKGROUND

It would be too ambitious pretending to come to a full understanding of the complex wrist joint in the present study. In order to explain the morphology of the carpal mechanism and to be able to deal with medical problems concerning the wrist joint, it is necessary to acquire a model of the wrist joint. Such a model should not only describe structures and phenomena, but should moreover be able to explain structures and phenomena. To explain means to determine causal relationships between form and function, in order to predict forms from functions and vice versa. The general, functional morphological form-function relationship states that the form, the component that has to be explained, is dependent on the function, the component that explains (Dullemeijer, 1974). This relationship can be further elaborated by stating that the forms of the parts of the musculoskeletal system depend on the motions that have to be carried out. The 'form' of this system refers to outer geometry of bone structures, to shape and structure, and also to material properties of connective tissue, to the relative positioning of connective tissues and of bones and to parameters characterizing muscles. Since changes in motion, can only be caused by forces, the parts of the musculoskeletal system have to generate or to transmit forces to be useful. Thus, two subdivisions of the form-function relationship arise, one stating that form depends on the force-transmitting or force-developing capacity required, the other stating that force transmission or development depends on the movements needed.

In short:

general relationship:		Form = f(Function)
relationship for musculoskeletal system:		Form = f(Motion)
subdividable relationship:		Form = f(force transmitting capacity) = f(Motion)
subdivided relationships:	1.	Form = f(Force transmitting capacity)
	2.	Force transmission = f(Motion).

Investigating these relationships means finding explanations for how forms are able to transmit forces and explaining how forces cause motions. Therefore, the forces that are transmitted or developed and the movements that result have to be studied.

APPLICATION TO THE WRIST JOINT

In the carpal joint two systems are available to transmit forces and to influence the carpal bone motions, the ligamentous system which can transmit forces by becoming strained, and the system of the carpal bone contact-areas, which can transmit forces by impingement. In the carpal joint no muscles are present which can directly influence the movements of the carpal bones relative to the forearm.

In this project the carpal ligamentous system will be studied in relation to the carpal bone movements. The present knowledge on form and behaviour of the carpal ligamentous system is limited. Forces, which are transmitted by carpal ligaments during *in vitro* or *in vivo* hand motions have not yet been determined. Concepts are found in the literature about length changes in the ligaments (Mayfield *et al.*, 1976; Bonjean *et al.*, 1981; Taleisnik, 1985), however, these concepts have been deduced from 2D notions on carpal motions, which have been shown to be invalid (Berger *et al.*, 1982; de Lange *et al.*, 1985; de Lange, 1987; *Ruby et al.*, 1988). De Lange *et al.* (1990c) developed a method to measure carpal ligament length changes *in vitro*. Concerning material properties of carpal ligaments more experimental work has been carried out compared to the work on ligament length change determinations. However these studies limit themselves often to determinations of failure loads or consider ligaments which are, due to their position within the joint, hard to measure *in situ* during *in vitro* motions (Mayfield et al., 1979; Logan *et al.*, 1986; Logan and Nowak, 1987; Nowak and Logan, 1991).

The first goal of this study will be to determine, in the same joint, carpal motions as well as ligament behaviour, *i.e.*, ligament straining, ligament material characteristics, and ligament forces.

Ligament behaviour is considered in this study mainly for pure flexion and deviation motions applied to the wrist joint. This has been the custom in biomechanical wrist-joint research. However, these selected movements do not cover the complete range of wrist-joint movements during activities of daily living (Palmer *et al.*, 1985). Hence, it is not sure whether the results thus acquired can give complete insight in the wrist-joint behaviour. As a second goal of this project the carpal motions and ligament length changes during hand motions covering the full range of the carpal joint are determined.

To summarize, in this study we will focus mainly on two aspects of the wrist-joint mechanism:

- the behaviour of selected carpal ligaments and, simultaneously, the motions of carpal bones will be documented during flexion and deviation of the hand.
- the elongations of the ligaments and the carpal kinematics in the full range of carpal motion will be studied.

SCOPE OF THE PRESENT STUDY

The first of these topics will be addressed in the chapters two to five. Together these chapters develop a method for estimating carpal ligament forces. Forces cannot be determined directly in the small carpal ligaments. Therefore a method has been developed by which this quantity can be estimated indirectly. The method is based on the rationale that the force transmitted by a ligament is related to the strain in that particular ligament. So, when at certain hand positions the ligament length, the stiffness and the length at which the ligament starts to transmit forces are known, the forces transmitted can be calculated. Finally in the sixth chapter the scope will be changed to the second topic, the assessment of the carpal motions and ligament behaviour in the full range of wrist-joint motion.

In the second chapter the recruitment patterns of selected carpal ligaments, *viz.* the length change patterns of these ligaments, and carpal motions during flexion and deviation of the hand are studied. Besides the mere documentation of the elongations occurring simultaneously to the motions of the carpal bones, this study focuses on mechanisms which provoke length changes in ligaments.

In the third chapter a method is presented for the assessment of the stiffness of the tiny carpal ligaments and the results of these determinations in fourteen wrist-joint specimens are documented. It is shown that carpal ligaments do not all consist of similar material.

To estimate the forces which are transmitted by a ligament when *ligament length changes and material characteristics are known, it is* necessary to know the length at which a ligament becomes strained. By the method to determine the zero-force length, that is the length at which a ligament becomes strained, the junction of the experimental set-ups of the preceding two chapters, resulting in the procedure for the estimation of ligament forces, is realized. The presentation of this technique, its accuracy and the discussion of the effects which preconditioning of the ligaments might have on the zero-force length, and consequently on the forces estimated, are treated in the fourth chapter.

The part of this thesis concerned with the ligament behaviour during flexion and deviation of the hand is concluded by the fifth chapter with the presentation of the force estimates for selected carpal ligaments.

In the sixth chapter, using known measurement techniques, the knowledge on kinematics of the carpal bones and ligament length changes is extended by the determinations of the movements of the carpals and elongations of the ligaments during hand movements covering the full range of wrist-joint motion. By using this knowledge it is checked whether current concepts on wrist-joint motion, which are deduced from flexion and deviation movements also hold true for the full range of movements. Concerning the ligaments, it is questioned whether the maximal elongations in flexion and deviation movements are also maximal for the full range movements.

Finally, in chapter seven a brief overview of the results will be presented, and some implications of the findings will be discussed.

HUMAN CARPAL LIGAMENT RECRUITMENT AND THREE-DIMENSIONAL CARPAL MOTION [1]

H.H.C.M. SAVELBERG, J.G.M. KOOLOOS, A. DE LANGE, R. HUISKES and J.M.G. KAUER

ABSTRACT-*In five fresh human cadaver wrist-joints six carpal ligaments and seven carpal bones were marked with small, radio-opaque pellets. Using a röntgenstereophotogrammetric measuring system the ligamentous length changes and the kinematics of carpal bones were determined in different flexion and deviation positions of the hand. The data generated by this method differ significantly from lengthening data predicted by current concepts on carpal ligament functioning. The motions of carpal bones and the lengthening of the carpal ligaments were related to each other. It appeared that most carpal ligaments lengthen only during one half of a full movement cycle. Hence, ligaments seem to constrain either a dorsal or a palmar directed motion of the hand, or either an ulnar or a radial directed motion of the hand. When the hand is in maximal radial deviation or maximal palmar flexion none of the ligaments has a greater length than in the neutral situation. The tested parts of the LunatoTriquetrum Palmar ligament do not lengthen during any movement of the hand. Significant lengthening relative to the neutral situation was found for the RadioCapitate Palmar ligament (6.5% in maximal ulnar deviation and 11.7% in maximal dorsal flexion of the hand), and for the distal string of the RadioLunate Palmar ligament (6.4% in maximal ulnar deviation). It was confirmed that the carpals, apart from moving in the plane in which the hand motion takes place, also execute considerable out-of-plane motions during hand motions.*

The combination of these experimental, simultaneously determined, data on length changes and on the movements of carpal bones are found to be necessary in order to give suitable explanations for the observed separate kinematical phenomena.

[1] Reprinted form *Journal of Orthopaedic Research*, **9**, 693-704, 1991.

INTRODUCTION

To understand the carpal mechanism underlying the motions of the hand relatively to the forearm, information on carpal kinematics and on carpal ligament lengthening is required. Carpal kinematics have been studied earlier (Berger *et al.*, 1982; de Lange *et al.*, 1985; Ruby *et al.*, 1988). The carpal ligament lengthening is a function of carpal displacement, the material characteristics of the ligaments and the positions of the ligaments relative to the carpals. Insight in carpal ligament behaviour and material characteristics will enable the deduction of forces, generated in the ligaments, by which knowledge on the carpal mechanism can be refined.

Most of the current concepts on carpal ligament length change (Mayfield *et al.*, 1976; Bonjean *et al.*, 1981; Taleisnik, 1985) are derived from 2-dimensional radiographs. These concepts are based on kinematical models of the wrist joint which assume 2D movements of the carpals in the principal planes only (flexion, deviation), whereby fixed axes of rotation during flexion and deviation are assumed (Mayfield *et al.*, 1976; Volz *et al.*, 1980; Youm *et al.*, 1980; Bonjean *et al.*, 1981; Fisk, 1984; Weber, 1984; Linscheid, 1986). In these studies usually one fixed axis is assumed for the movement of the whole carpal joint for flexion and one for deviation of the hand. All carpal bones are thought to rotate around these axes when the hand is deviated or flexed. For example, during radial deviation of the hand relative to the forearm, the carpals of the distal row (trapezium, trapezoid, capitate and hamate) are assumed to rotate around one rotation axis in the capitate head towards the radial side, while those of the proximal row (scaphoid, lunate and triquetrum) are assumed to move ulnarly around the same axis. However, as shown experimentally (Berger *et al.*, 1982; de Lange *et al.*, 1985; Ruby *et al.*, 1988), carpals also demonstrate considerable out-of-plane motions in planes perpendicular to the one in which the hand moves. Furthermore, these authors (Berger *et al.*, 1982; de Lange *et al.*, 1985; Ruby *et al.*, 1988) do not find a fixed centre of rotation. Hence, for a good comprehension of ligament behaviour, it needs to be studied in three-dimensional analysis.

The purpose of the present project was to update the present-day concepts, using precise measurement techniques for ligament lengthening behaviour and 3D carpal motion. These techniques are based on röntgenstereophotogrammetry, whereby markers in bones and ligaments are reconstructed from stereoröntgen images (Blankevoort *et al.*, 1988; de Lange *et al.*, 1985; Selvik, 1974).

METHODS AND MATERIALS

Nomenclature

In this study five fresh human cadaver wrist-joints were used, and were kept frozen until time of use. This procedure did not seem to affect the mechanical properties of the ligaments (Woo *et al.*, 1986). By means of radiographs each specimen was examined for osseous abnormalities before the experiment.

The superficial ligamentous apparatus of the carpal joint can be characterized as a complex system of interwoven ligament fibres (Figure 2.1B), as it is presented for example by Williams and Warwick (1980), rather than as a system of well defined ligaments, as some authors suggest (Taleisnik, 1976; Mayfield *et al.*, 1976; Bonjean *et al.*, 1981). For practical purposes this study is limited to the superficial ligament complex. This system can be reached without inducing functional abnormalities in the carpus as a whole. For this study the complex was subdivided in strips of ligamentous tissue based on the patterns of attachment areas on the carpal bones. In each specimen six such strips were defined (Figure 2.1B), four on the palmar and two on the dorsal side. As is customary in the literature (Mayfield *et al.*, 1976; Taleisnik, 1985), they were named by their origin and insertion sites respectively. For easy-reading purposes an extra 'P' or 'D', for 'palmar' or 'dorsal', respectively, was added to the abbreviations. Hence, the following ligament strips were distinguished (between brackets Taleisnik's (1985) nomenclature): RadioCapitate Palmar (RadioScaphoCapitate), RadioLunate Palmar, LunatoTriquetrum Palmar, TriquetroCapitate Palmar (Volar InterCarpal), RadioTriquetrum Dorsal (Radiotriquetral fascicle of the Dorsal RadioCarpal ligament) and TriquetroTrapezium Dorsal (Dorsal InterCarpal). As some of these strips were rather wide, differences in length changes between the outermost fibres (distal and proximal parts) can be expected. In these cases both these strip parts were considered and coded by a minor 'p' or 'd', for 'proximal' or 'distal' strings respectively.

Surgical proceedings and marking of selected elements.

By a transversal skin incision just proximal to the wrist joint and a longitudinal incision crossing the first one, the joint was approached. The skin of the forearm was opened and the tendons of the *mm. flexor carpi radialis* and *ulnaris*, the *mm. extensor carpi ulnaris* and *radialis longus* and *brevis*, the *m. extensor digitorum* and *mm. extensor pollicis longus* and *brevis*, the *mm. flexor digitorum superficialis* and *profundus* and *m. abductor*

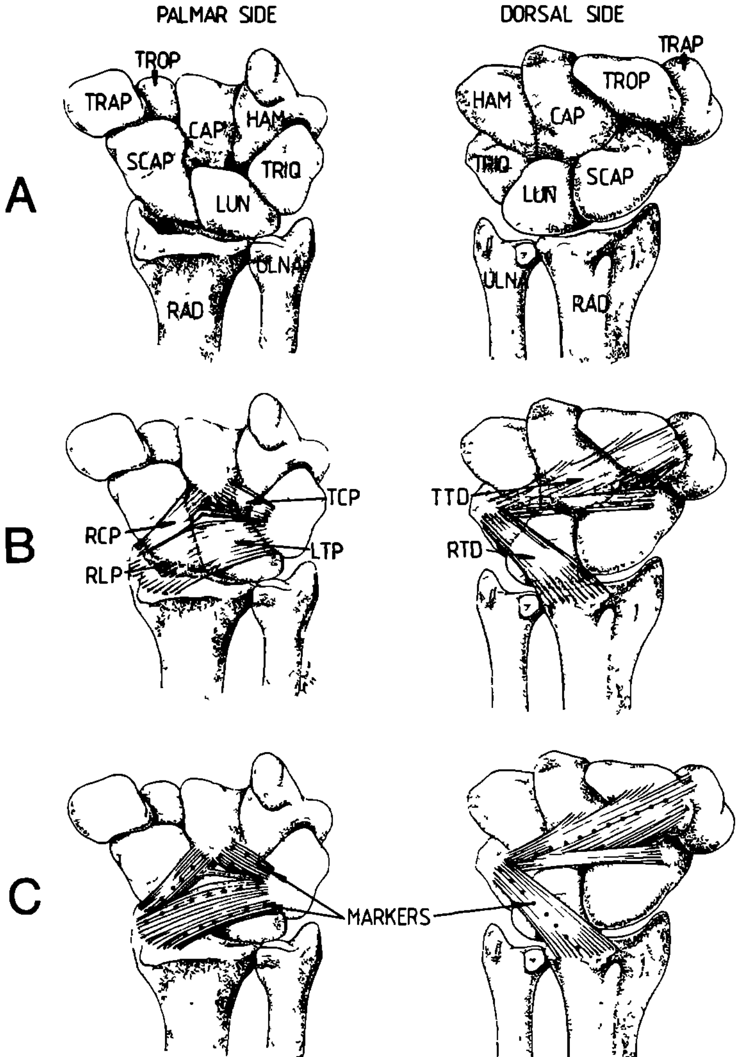

Figure 2.1 *Schematic view of the tested carpal system.*
A: The carpal bones from the palmar (left) and the dorsal side (right).
B: The tested carpal ligaments from the palmar (left) and the dorsal side (right).
C: The distribution of the radio-opaque markers over the carpal ligament system; left palmar, right dorsal side. Wider ligament strips are provided with two strings of markers, a proximal and a distal one. (Denotations: RAD: radius; TRAP: trapezium; TROP: trapezoid; CAP: capitate; HAM: hamate; SCAP: scaphoid; LUN: lunate; TRIQ: triquetrum; RCP: RadioCapitate Palmar strip; RLP: RadioLunate Palmar strip; LTP: LunatoTriquetrum Palmar strip; TCP: TriquetroCapitate Palmar strip; RTD: RadioTriquetrum Dorsal strip; TTD: TriquetroTrapezium Dorsal strip).

pollicis longus were isolated. The longitudinal incision was extended in the distal direction. Subsequently the flexor retinaculum was divided so that the tendons could be moved distally and the ligament system exposed. A similar action was undertaken at the dorsal side of the joint.

Four to six tantalum or stainless steel markers (diameter(∅): 0.5, 0.8 or 1.0 mm) were introduced into each of the seven carpal bones and into the radius. To insert the markers a special spring actuated syringe was used (Aronson *et al.*, 1974). Very small incisions were made in each ligament fibre to create envelopes for tantalum pellets (∅: 0.5 mm), which were to represent the ligament strips. After the markers were placed, these envelopes were covered by a small dot of tissue glue (Histoacryl®, B.Brown AG, Melsungen, FRG) to prevent the markers from being squeezed out of the fibres. Because the dots of tissue-glue are rather small relative to the ligament dimensions, their effects on the ligamentous material characteristics are assumed to be neglegible. Each strip was presented by at least three markers; one each on the origin and insertion site, and the third between those two. In most cases a total of four or five tantalum pellets were introduced. Experiments by de Lange *et al.* (1990c) showed that this is a reliable and valid method. Care was taken that a string of markers was placed along one and the same fibre, close to the middle of the ligament. The wider ligament strips (RadioLunate Palmar, LunateTriquetrum Palmar and TriquetroCapitate Palmar) were provided with two strings of markers. In these cases the outermost fibres were chosen to represent the ligaments (Figure 2.1C). Finally, the retinacula and the skin were closed by suturing.

Experimental set up and data processing

The specimen was positioned into a motion-guiding system (de Lange *et al.*, 1985). The radius was fixed, and the third metacarpal was connected to a moveable carriage by a Steinmann pin, which guided the flexion and deviation movements of the hand. The tendons acting on the hand were loaded by 20 N constant-force springs to simulate the assumed stabilizing activity of these muscles. The forearm was supinated. De Lange *et al.* (1985) and de Lange (1987) showed that no differences in carpal kinematics occur between pronated and supinated test-specimens. Starting from an extreme position (*e.g.* maximal palmar flexion) the hand was moved in four-degree steps to the other extreme (dorsal flexion in this example) and back to the starting position. A similar procedure was followed for the movement through the other plane, deviation. After each 4-degree step, a pair of stereoröntgenographs was made by two x-ray tubes. A more detailed description of the experimental set-up is given by de Lange *et al.* (1985) and de Lange (1987).

The röntgenstereophotogrammetric experiment resulted in about 80 pairs of stereoröntgenographs for a complete flexion cycle and 40 pairs for a deviation cycle. The markers, representing the carpal bones and ligaments on the röntgenographs, were digitized. Using stereophotogrammetric principles (Selvik, 1974) the 3D positions of the tantalum pellets were reconstructed for each carpal position. The sequential position data were used to determine the 3D motion characteristics of each carpal, in terms of translation vectors and Euler rotations, or in terms of helical axes (de Lange, 1987; de Lange *et al.*, 1990a), and the lengths of the carpal ligaments as the sum of distances between subsequent ligament markers (de Lange *et al.*, 1990c).

Calculation of the kinematic parameters and the ligament strains

The total length of a ligament string in a particular position j, L_j, is given by the sum of the lengths of subsequent marker intervals according to

$$L_j = \sum_{i=1}^{n} |x_{j,i} - x_{j,i-1}| \qquad (2.1)$$

where $x_{j,i}$ is the position vector of the i-th marker of a ligament string, measured with the hand in position j, L_j is the total length of the ligament string with the hand in position j, i is the marker number ($1<i<n$), and j is the position number ($1<j<m$).

Furthermore, the relative length change of a ligament string (e_j) is calculated as the length of that ligament string in position j relative to its reference length, which is defined as the length in the neutral position of the hand, when radius and third metacarpal are aligned. This neutral position is determined visually. The reference does not necessarily equal a functional 'zero-length', a situation in which the ligament force is zero.

The relative length is determined by:

$$e_j = \left(\frac{L_j}{L_o}\right) \times 100\% \qquad (2.2)$$

where L_o is the total length of the ligament string with the hand in the neutral position.

The length changes of the ligament strings are presented as functions of the degree of flexion or deviation of the hand, which is represented by the capitate position (de Lange *et al.*, 1985; de Lange, 1987).

Finite helical axes are calculated for the movements of the carpals from the neutral position to the four end positions, radial and ulnar deviation, palmar and dorsal flexion. These helical axes describe the movement of a particular carpal bone relative to another carpal or to the radius, as a combination of rotation about and translation along the axis. Furthermore, to relate these data to the ligament length change information, finite helical axes for each movement are averaged over the five different experiments. This results in one average finite helical axis, the angular dispersion (X) of the five actual finite helical axes around the average finite helical axis, and the mean and standard deviation for the magnitude of rotation about and translation along the actual finite helical axes for each movement. The direction vector of the average finite helical axis is calculated according to a method minimizing the root mean square (r.m.s.) values of the sinuses of the angles between the average finite helical axis and the actual finite helical axes (de Lange, 1987; de Lange *et al.*, 1990a; Woltring, 1990). The angular dispersion (χ (chi)) is defined as the arcsine of the r.m.s. values.

Analysis of bone-ligament interaction

The length of a ligament can be changed by two causes. Firstly, by displacement of the insertion sites of the ligament relative to each other, and secondly when the course of a ligament is changed by an intervening carpal bone. In the latter case the ligament is forces to bent around a bone. The scaphoid could be such a bone; it shows relatively much freedom of movement and several ligaments cross this bone without attaching to it (RCP, RLP). The same can be said for the TCP ligament and the hamate.

To analyse these interactions for each ligament, three-dimensional graphs of spatial ligament courses, which are represented by the marker positions on the ligament as measured in ultimate hand positions, are produced. The positions of the markers in the neutral and an extreme hand position are presented. These plots represent the ligament string and show an image of the course of that ligament. The establishment of the changes of these courses and of the marker positions between the neutral and one of the extreme positions of the hand enables a discussion of bone-ligament interaction.

RESULTS

Ligament length changes

From the mean ligament length changes it appears that all the ligament strings are recruited during only one direction of a movement (Table 2.1). They lengthen either when the hand is deviated radially or when it is deviated ulnarly and either when it is flexed palmarly or when it is flexed dorsally. It can also be observed that some elements (proximal and distal LunateTriquetrum Palmar) do not show any length change at all, in any of the motions.

In flexion, the maximal length changes for RadioCapitate Palmar, proximal and distal RadioLunate Palmar and RadioTriquetrum Dorsal strings are significantly higher ($p<0.0625$, Wilcoxon's test for paired comparison) than in deviation. The other selected elements of the carpal ligamentous system do not show significant differences in maximal length changes between flexion and deviation movements of the hand.

In maximal radial deviation no strings are significantly stretched relative to the neutral situation. The TriquetroCapitate Palmar strings even shorten significantly ($p<0.01$, *t*-test) in this situation. In maximal ulnar deviation of the hand, significant ($p<0.05$) elongations are observed in the RadioCapitate Palmar, distal RadioLunate Palmar, proximal TriquetroCapitate Palmar and TriquetroTrapezium Dorsal strings.

In maximal dorsal flexion of the hand, the RadioCapitate Palmar, proximal and distal RadioLunate Palmar and proximal TriquetroCapitate Palmar strings are recruited ($p<0.1$). The RadioTriquetrum Dorsal string shortens significantly ($p<0.05$) in this situation. In maximal palmar flexion no lengthening of ligamentous strings can be noticed. The RadioCapitate Palmar, distal RadioLunate Palmar and TriquetroCapitate Palmar strings are significantly ($p<0.05$) shorter in maximal palmar flexion.

The length changes of the strings between the neutral and the extreme positions occur gradually in general (Figure 2.2). Only in the less stretched situations some wrinkles appear on the curves. In most of the strings, continuous length changes occur from a certain point in the hand position to the extreme of the motion. Some reach a maximum or minimum length before the hand position has reached its extreme value. This phenomenon occurs only in deviation movements for the RadioTriquetrum Dorsal, proximal and distal TriquetroCapitate Palmar strings.

For the wider ligament strips that are represented by two strings of markers, a proximal and a distal one, we can observe in several situations significant differences in the length changes of both these strings (Table 2.1). In ulnar deviation the distal RadioLunate Palmar string lengthens, while the

Table 2.1 The means and standard deviations (between brackets) of relative length changes of the wrist-joint ligaments in the extreme positions of the hand relative to the neutral in percentages. Length changes which differ significantly from 100%, which equals the 'neutral' length, are marked with asterisks, denoting a significance level of 0.05 for a t-test.

	Deviation				Flexion			
	% Mean ulnar (±sd)	n	% Mean radial (±sd)	n	% Mean palmar (±sd)	n	% Mean dorsal (±sd)	n
RCP	106 5(2 3)*	5	101 1(2 1)	5	89 0(6 4)	5	111 7(4 8)	5
RLPp	102 0(3 1)	5	100 0(1 0)	5	89 5(8 7)	5	103 3(2 0)	5
RLPd	106 4(3 4)*	5	99 6(1 0)	5	92 2(3 4)*	5	107 6(5 3)	5
LTPp	99 2(1 6)	4	100 0(1 1)	4	99 5(2 1)	4	100 9(0 6)	4
LTPd	100 5(0 6)	4	98 8(0 9)	4	98 7(1 5)	4	100 7(0 4)	4
TCPp	105 4(3 1)	2	97 0(0 6)*	3	101 3(2 5)	3	103 9(0 9)*	2
TCPd	96 5(0 9)*	2	97 4(0 3)*	3	100 6(2 3)	3	102 6(3 4)	3
TCP	88 8(1 8)*	2	96 8(1 1)*	2	94 0(1 4)*	2	101 8(1 1)	2
RTD	95 6(2 9)	5	98 8(0 9)	5	105 7(5 0)	5	95 2(2 3)*	5
TTD	106 4(4 3)	3	99 2(0 8)	3	101 9(6 1)	3	98 7(2 0)	3

proximal RadioLunate Palmar string does not change in length; the distal TriquetroCapitate Palmar string becomes shorter, while the proximal TriquetroCapitate Palmar string retains its 'neutral' length. In palmar flexion the same trend is shown for both the RadioLunate Palmar strings; in dorsal flexion a lengthening of the proximal TriquetroCapitate Palmar string was noticed, while the distal string did not change in length.

Carpal motions

The kinematic parameters for the carpal motions show that considerable out-of-plane movements of the carpals occur during flexion and (in particular) deviation of the hand (Table 2.2). In flexion movements of the hand, the carpal bones usually show only small tendencies to move in other than the flexion plane. But in palmar flexion, out-of-plane motions (ulnar deviation and supination) can be noticed for the movement of the lunate relative to the radius. The out-of-plane movements of the other carpals relative to the radius are only slight. On the other hand, in both ulnar and

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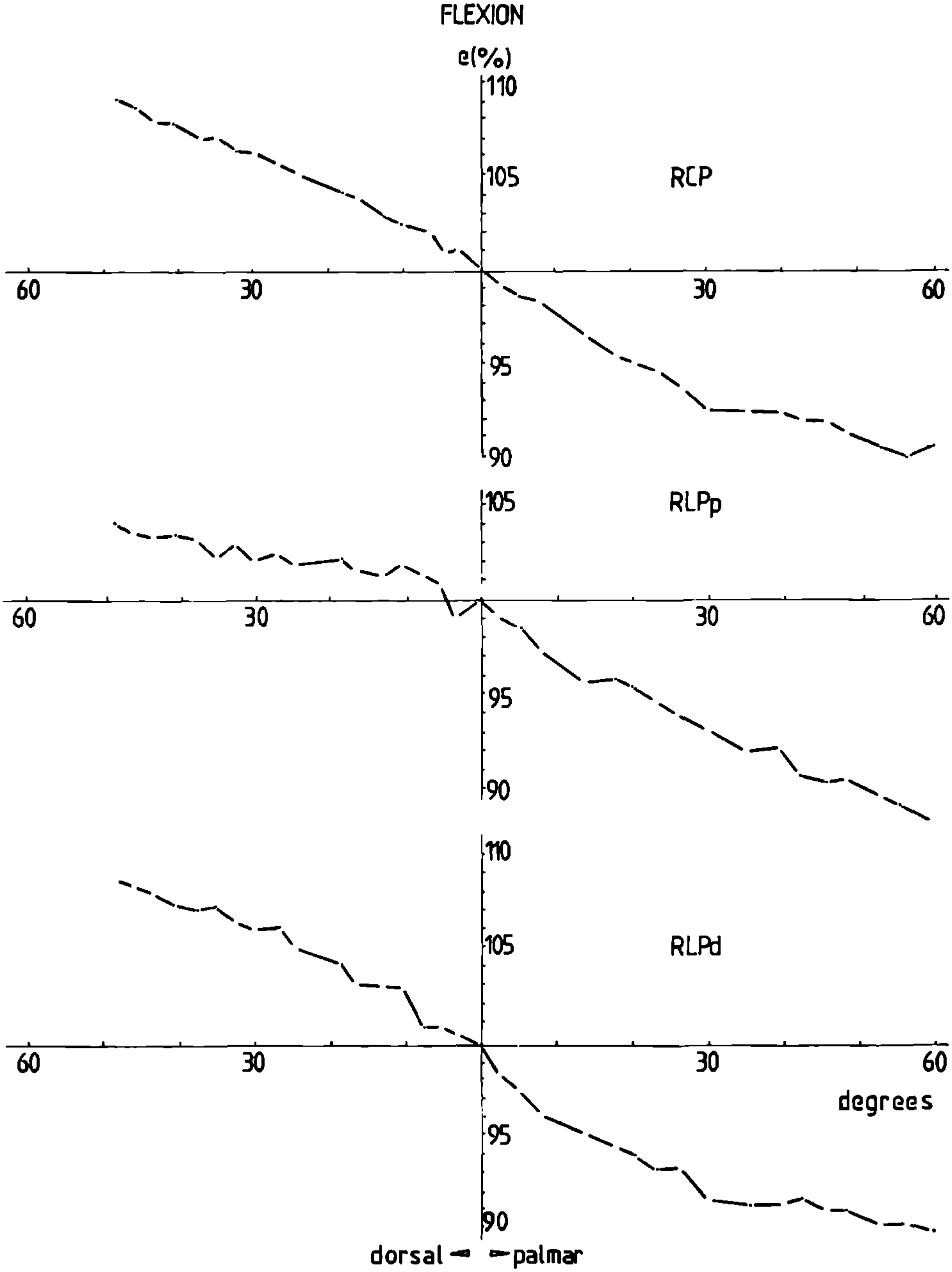
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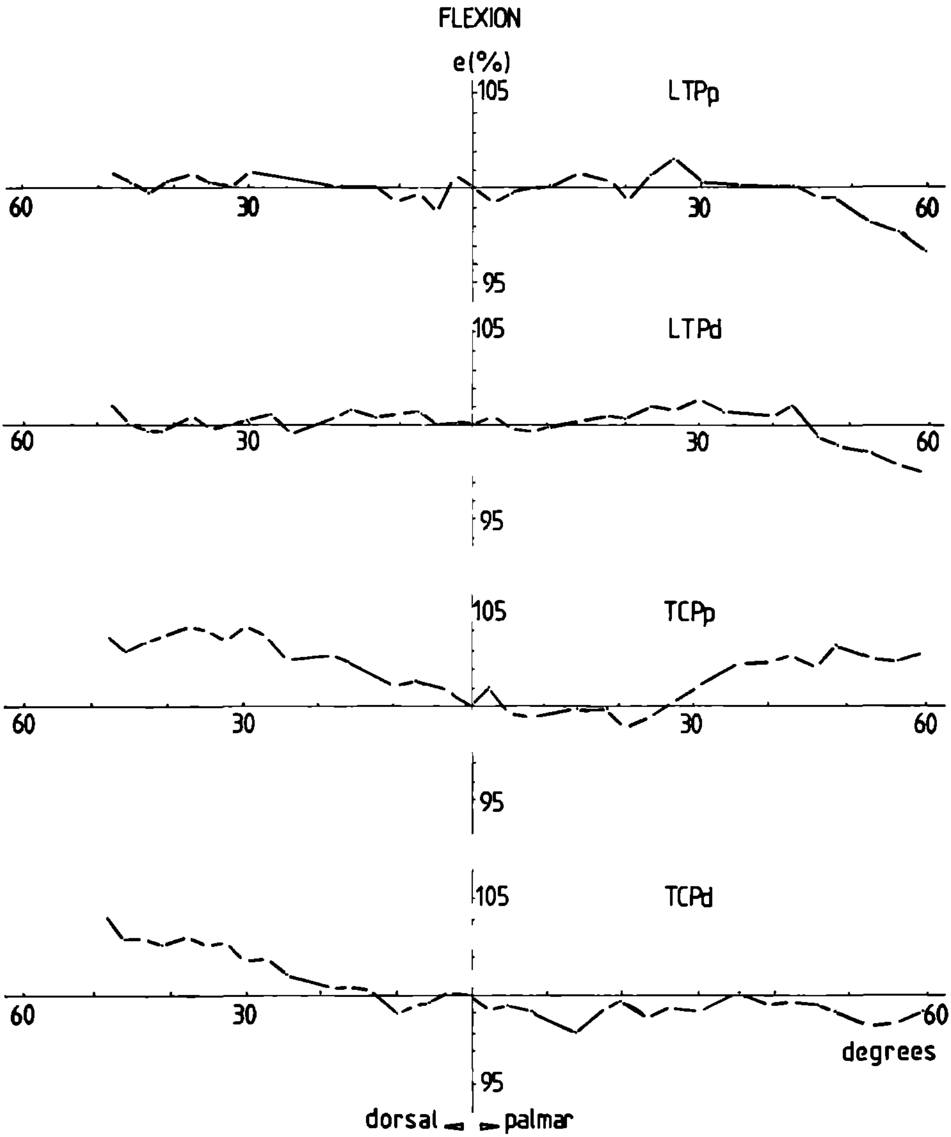
dorsal
palmar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dorsal
palmar

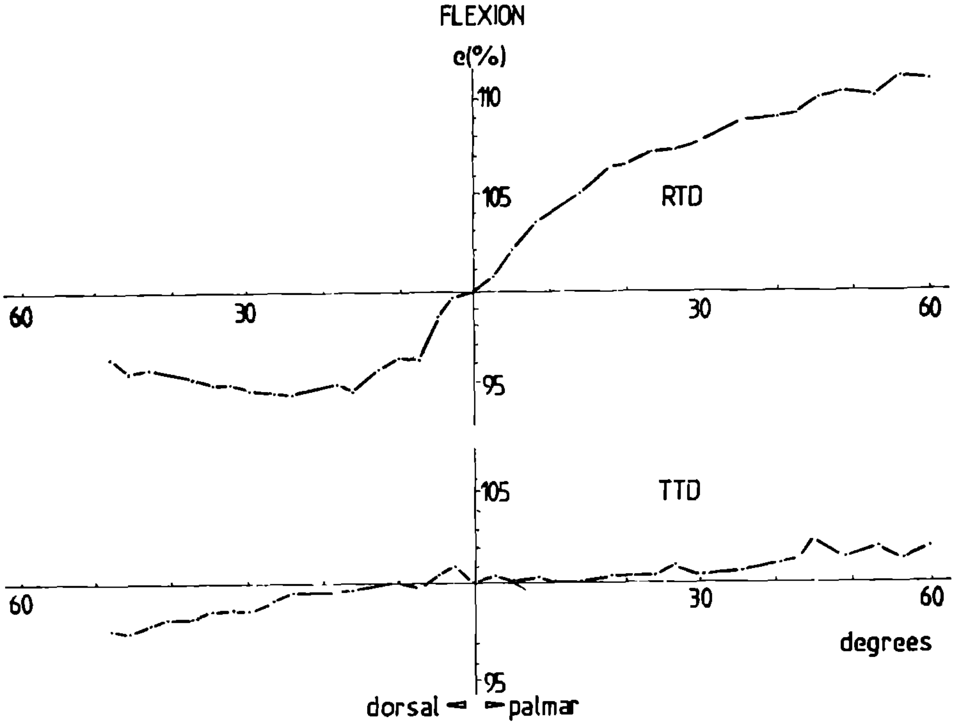
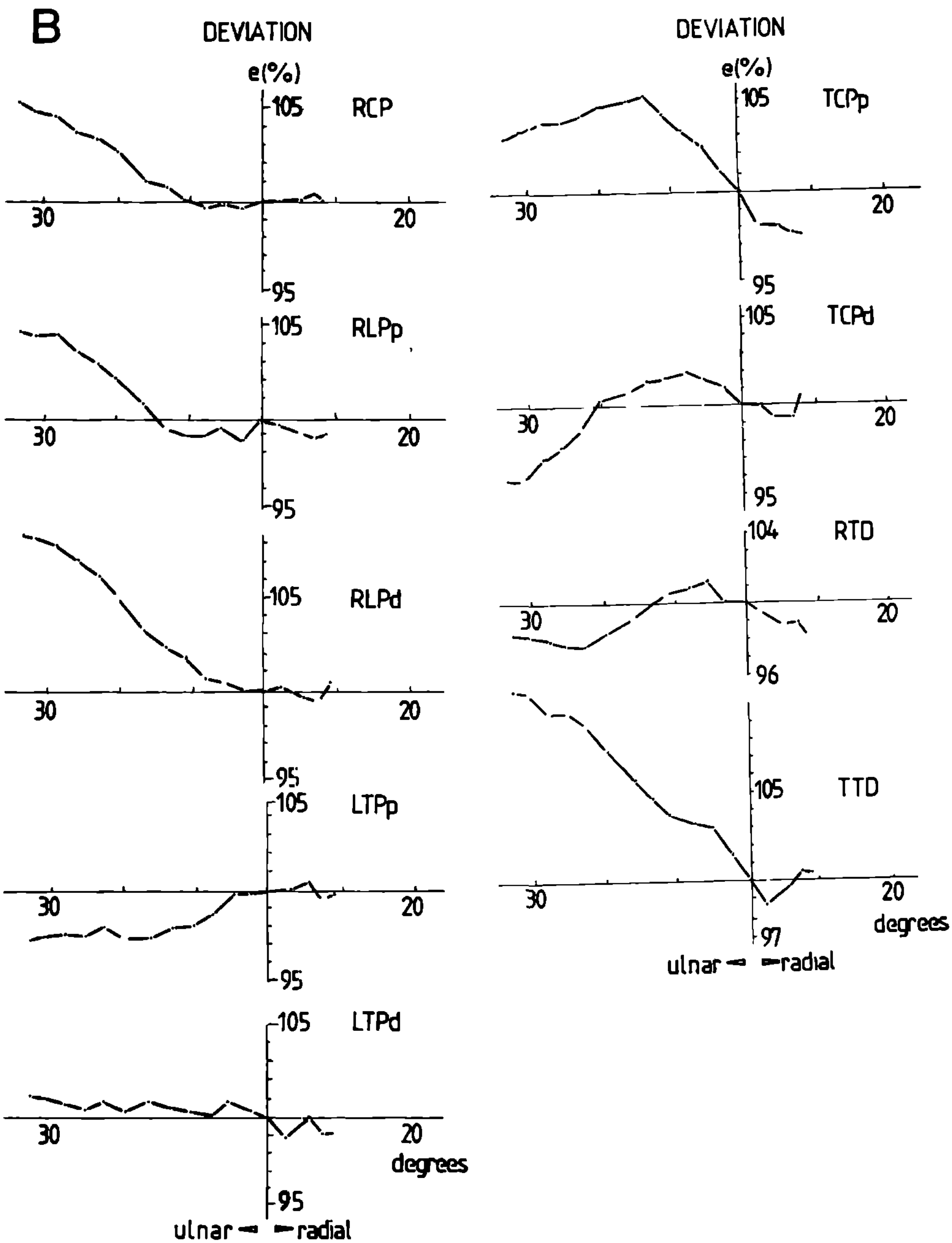


Figure 2.2 *Typical ligament recruitment patterns of nine marked ligament fibres in six ligaments as a function of applied hand motion. See for denotations figure 1.*
A: The relative length changes as a function of flexion of the hand.
B: The relative length changes as a function of deviation of the hand (next page).


B
DEVIATION
e(%)
105
RCP
30
20
95
105
RLPp
30
20
95
105
RLPd
30
20
95
105
LTPp
30
20
95
105
LTPd
30
20
degrees
95
ulnar radial
DEVIATION
e(%)
105
TCPp
30
20
95
105
TCPd
30
20
95
104
RTD
30
20
96
105
TTD
30
20
degrees
97
ulnar radial

radial deviation, the movements of the lunate and the scaphoid relative to the radius have a notable out-of-plane component. Here the out-of-plane component, flexion in these cases, is even higher than the planar component. Furthermore, in radial deviation the other (triquetrum, trapezium, trapezoid, capitate and hamate) carpals and in ulnar deviation the triquetrum and the hamate show less pronounced out-of-plane motions, similar to those in palmar flexion.

The excursions of the carpals, *i.e.* the total rotations about and, to a lesser extent, the translations along the finite helical axis, are more extensive for flexion than for deviation.

Table 2.2 The unit-vector components in x-, y- and z-direction of the mean finite helical axes, the rotations about and the translations along them, for the movement from the neutral position to one of the extreme positions of hand motion of several carpals and the radius relative to each other. Between brackets standard deviations. The column denoted by χ gives the angular dispersion as a measure of the deviation of the actual finite helical axes from the average finite helical axis. For deviation movements of the hand positive unit-vector components correspond with radial deviation, palmar flexion and pronation for x, y and z respectively, for flexion movements of the hand positive components of x, y and z correspond to palmar flexion, radial deviation and supination respectively.

	Average finite helical axis unit-vector components			χ	Rotation	Translation
	x	y	z	(degree)	(degree(± sd))	(mm(± sd))
Neutral to ulnar deviation						
Lunate to radius	-0.45	-0.89	0.10	10.29	34.2(4.2)	-2.1(1.1)
Capitate to radius	-0.99	0.01	0.11	10.51	43.6(7.2)	-5.6(1.5)
Scaphoid to radius	-0.44	-0.89	0.13	8.53	35.3(7.3)	-2.0(1.2)
Trapezium to radius	-0.99	0.09	0.07	11.91	44.6(9.1)	-6.7(2.1)
Trapezoid to radius	-1.00	-0.04	0.05	12.61	40.9(7.2)	-6.1(1.4)
Triquetrum to radius	-0.71	-0.70	0.05	28.50	38.1(10.1)	-1.3(1.3)
Hamate to radius	-0.95	-0.27	0.18	16.50	39.8(10.8)	-3.0(2.1)
Triquetrum to lunate	-0.60	0.80	-0.07	25.23	18.4(19.8)	-0.2(0.4)
Capitate to triquetrum	-0.50	0.78	0.38	27.42	29.5(8.3)	-0.1(0.8)
Trapezium to triquetrum	-0.43	0.84	0.32	29.31	30.9(11.7)	-0.7(0.5)

Neutral to radial deviation						
Lunate to radius	0 25	0 96	-0 01	12 10	8 2(2 8)	0 1(0 1)
Capitate to radius	0 94	0 12	-0 30	7 78	14 6(2 8)	1 0(0 5)
Scaphoid to radius	0 18	0 98	0 01	15 43	9 6(2 8)	-0 1(0 2)
Trapezium to radius	0 92	-0 09	-0 39	6 21	16 2(2 9)	1 8(0 8)
Trapezoid to radius	0 93	-0 04	0 36	8 01	14 6(2 9)	-1 5(0 6)
Triquetrum to radius	0 95	0 30	-0 07	40 37	8 8(2 6)	0 2(0 6)
Hamate to radius	0 94	0 20	-0 27	11 15	15 2(2 8)	1 0(0 5)
Triquetrum to lunate	0 74	0 62	0 28	42 62	7 6(3 0)	-0 4(0 3)
Capitate to triquetrum	0 90	0 38	-0 21	21 30	11 8(5 6)	0 1(0 6)
Trapezium to triquetrum	0 79	-0 59	-0 20	17 58	14 4(6 5)	-0 1(0 7)
Neutral to palmar flexion						
Lunate to radius	0 78	-0 45	0 44	9 64	27 1(8 2)	0 7(1 5)
Capitate to radius	0 95	-0 22	0 21	10 86	69 9(14 5)	-0 2(1 0)
Scaphoid to radius	0 93	-0 26	0 28	7 96	43 2(7 9)	-0 8(1 1)
Trapezium to radius	0 94	-0 18	0 28	15 37	61 1(9 7)	-0 9(1 7)
Trapezoid to radius	0 93	-0 16	0 35	24 42	83 1(34 5)	1 6(3 5)
Triquetrum to radius	0 92	0 33	0 20	9 35	35 4(11 3)	0 8(1 3)
Hamate to radius	0 93	0 23	0 27	9 75	68 9(13 7)	0 2(1 2)
Triquetrum to lunate	0 84	0 45	-0 30	10 27	13 1(8 3)	-0 04(0 5)
Capitate to triquetrum	0 98	0 05	0 20	16 37	36 0(7 4)	0 4(0 8)
Trapezium to triquetrum	0 88	0 40	0 24	26 39	30 2(6 5)	0 7(1 2)
Neutral to dorsal flexion						
Lunate to radius	0 99	0 04	-0 14	26 58	36 4(11 5)	-1 3(0 1)
Capitate to radius	1 00	0 06	0 04	27 67	62 4(6 6)	1 4(0 8)
Scaphoid to radius	0 99	0 09	0 07	27 01	57 1(9 9)	1 5(0 3)
Trapezium to radius	1 00	0 08	-0 04	27 35	59 4(6 1)	-2 0(1 3)
Trapezoid to radius	-0 99	0 09	0 07	26 96	62 5(6 9)	1 8(0 9)
Triquetrum to radius	0 99	0 14	-0 07	28 07	51 2(27 6)	-1 0(1 4)
Hamate to radius	-0 99	0 09	0 10	30 06	61 7(6 9)	-1 5(0 7)
Triquetrum to lunate	-0 98	0 16	0 10	36 74	10 3(2 6)	0 1(0 1)
Capitate to triquetrum	-0 85	0 35	-0 39	32 02	23 5(7 4)	0 3(0 5)
Trapezium to triquetrum	0 84	0 32	0 45	35 63	20 8(7 9)	0 1(0 1)

Bone-ligament interaction

Now that the ligament recruitment patterns (Figure 2.2) and the motions of the carpal bones (Table 2.2) are established, we will consider the way in which the carpal motions influence the ligament length.

Flexion

When the hand is flexed palmarly, the insertion sites of ligaments that run on the palmar side of the hand between the radius and the carpals approach each other and consequently almost all these ligaments become shorter (RCP, RLPp and RLPd), except the TCP and LTP ligaments that retain their lengths. This is illustrated in Figure 2.3B for the RCP ligament. In this case there are no effects of an intervening bone measured. The same occurs for the ligaments on the dorsal side of the hand during dorsal flexion of the hand (RTD, TTD). During dorsal flexion the ligaments on the palmar side (RCP, RLPp, RLPd and TCP) all elongate because the distances between their insertion sites increase, except the ligament LTP which does not change. The RCP ligament elongates even more due to an intervening bone, the scaphoid. This is illustrated in Figure 2.3C. This ligament not only elongates because of the separation of the radius and the capitate (Figure 2.3C and D: the distal marker has mainly moved dorsally (from 5→5')), but also because the ligament is pushed away by the scaphoid (Figure 2.3C and D: the distal displacement of the middle marker (from 3→3')). The dorsal ligaments (RTD, TTD) elongate in palmar flexion because the distances between their insertion sites increase. The LTP is not affected by the flexion of the hand because the lunate and triquetrum, to which it inserts, move more or less similarly.

Deviation

When the hand is moved radially the lengths of the ligaments are not changed. This is due to the movements of the carpals, which are very small in this case, hence the insertion sites are hardly displaced. During ulnar deviation the shortening of the RTD ligament is caused by the decrease of the distance between the respective insertion sites. The shortening of the TCP ligament can also be attributed to the approach of the insertion sites. The movements of the lunate and the triquetrum in ulnar deviation are about equal, so there is no change in the distance between the insertion sites of the LTP ligament and in the length of this ligament. The insertion sites of the TTD ligament are separated during ulnar deviation, hence the ligament elongates.

The RCP ligament elongates because of the displacement of the insertion sites of the ligament and because of an intervening bone, the scaphoid, which displaces the ligament distally. This is illustrated in Figure 2.3E and F for the RCP ligament. In this figure the arrow, showing the displacement of the most distal marker (from 5→5'), denotes dorsal as well as ulnar displacement of the insertion on the capitate. This means that the distance between origin and insertion is increased by the movement of the capitate relative to the radius. Furthermore, the middle part of the ligament has been lifted distally (Figure 2.3E and F: arrow associated with the middle marker (from 3→3')), which indicates the intervening effect of the scaphoid.

A hitherto unknown ligament-bone interaction in the carpus is shown in relation with the RLP ligament. Although both the distal and the proximal strings of the RLP ligament insert to the same bones (radius and lunate), their lengths change unequally during ulnar deviation. The RLPd is elongated because the distance between the insertion sites increases, while the RLPp shortens due to the approach of its insertion sites to each other. This is illustrated in Figure 2.4B and D. The out-of-plane motion of the lunate (dorsal flexion, Table 2.2A) displaces the insertion site of the proximal string distally and somewhat palmarly (Figure 2.4B), and as a consequence the distance between origin and insertion decreases. However, the insertion site of the distal string of the lunate is displaced mainly distally (Figure 2.4D), due to the same out-of-plane motion, causing an increase of the distance between origin and insertion.

DISCUSSION

Assessment of the measuring method

For the measurement of ligament length changes de Lange *et al.* (1990c) have shown, that the method used in this experiment is to be preferred above determination of ligament length by measuring the origin-insertion interval. The advantage of the present method is the accommodation to fibre curvature without impairing ligament or carpal bone movements. To determine errors due to inaccuracies in the data processing, six subsequent pairs of röntgenographs were processed five times. The standard deviations of the string lengths were chosen as a measure for the error. They ranged from 0.005 to 0.055 mm. The standard deviations for the relative string lengths ranged between 0.037 and 0.158%.

A similar procedure for the determination of the accuracy of the kinematical parameters was carried out by de Lange *et al.* (1985, 1990) and de Lange (1987). They registered 2.97 degrees for the standard deviation of the direction of the finite helical axis, 0.23 degrees for the standard deviation of the rotation about the finite helical axis and 0.025 mm for the

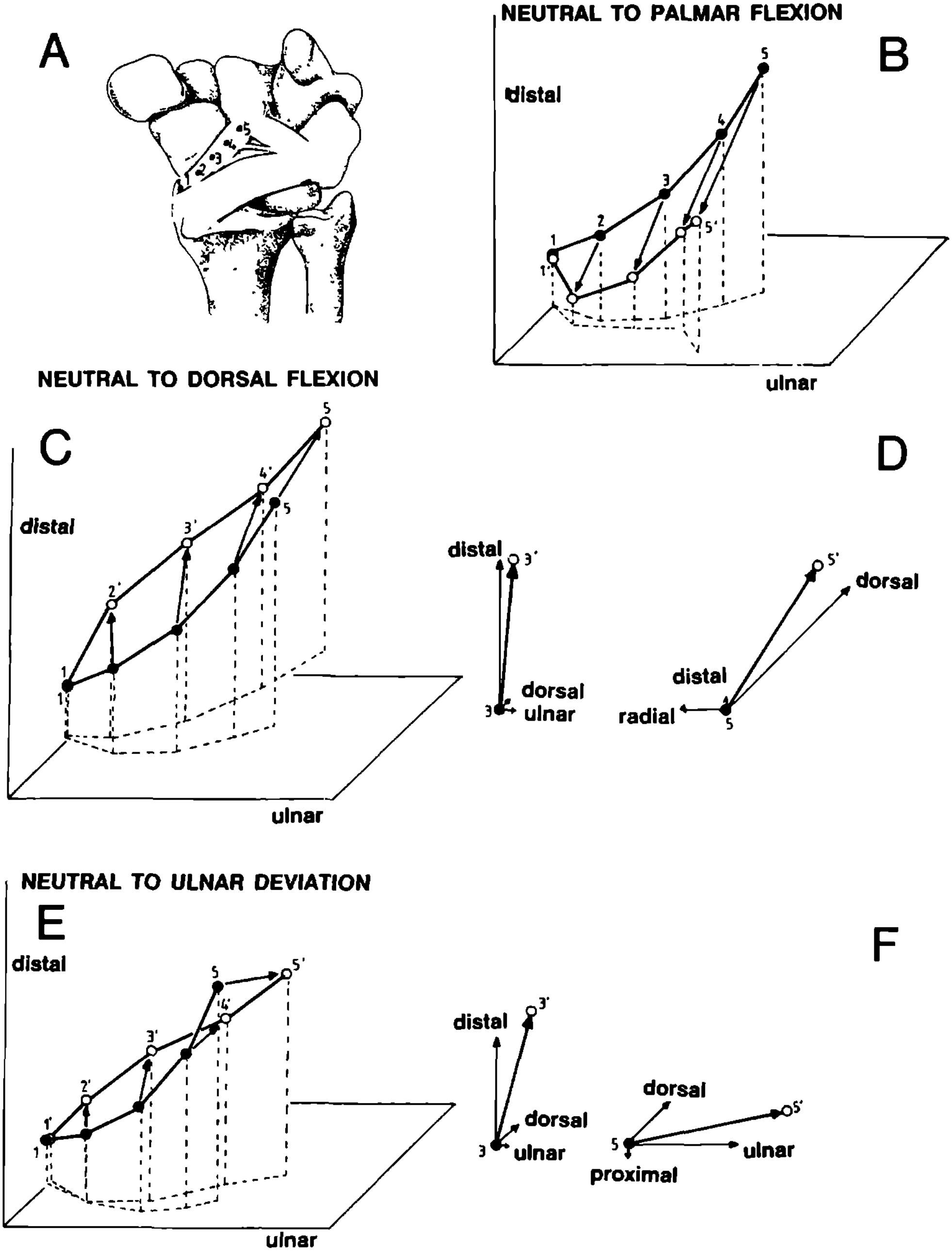

A
NEUTRAL TO PALMAR FLEXION
B
distal
ulnar
NEUTRAL TO DORSAL FLEXION
C
distal
ulnar
D
distal
dorsal
ulnar
distal
dorsal
radial
NEUTRAL TO ULNAR DEVIATION
E
distal
ulnar
F
distal
dorsal
ulnar
dorsal
ulnar
proximal

Figure 2.3 The 3D kinematics of the RCP ligament. The positions of the ligament markers and the 3D course of the RCP ligament are given.
A: The position of the RCP ligament relative to the other carpal structures.
B: The positions of the markers in the neutral position (•) and in the palmarly flexed position of the hand (○). The solid lines between the markers in a hand position show the interpolated course of the ligament, the arrows between two positions of a marker in different positions of the hand represent the motions of the markers due to palmar flexion of the hand. The markers are numbered from proximal to distal in an increasing order. In the neutral position the markers are primeless, whereas in palmar flexion they are primed.
C: Similar to Figure 2.3B but now for dorsal flexion instead of palmar flexion of the hand.
D: The displacement of the middle marker (3→3') and the most distal one (5→5'), showing respectively mainly distal displacement, denoting the increased curvation of the ligament and mainly dorsal displacement, representative for the increased distance between origin and insertion.
E: Similar to Figure 2.3B but now for ulnar deviation instead of palmar flexion of the hand.
F: Similar to Figure 2.3D but now for ulnar deviation instead of dorsal flexion of the hand. Again showing increased curvation and distance between origin and insertion.

standard deviation of the translation along the finite helical axis. These errors are small enough not to interfere with our conclusions.

Carpal kinematics and ligament length referred to other studies

The present results on carpal movements are in good agreement with earlier studies (Berger *et al.*, 1982; de Lange *et al.*, 1985; Ruby *et al.*, 1988). Notably, considerable out-of-plane motions of the proximal carpals (scaphoid, lunate and triquetrum) are observed in ulnar and radial deviation and, to a somewhat lesser degree, in palmar flexion. Hence, the carpal motions can hardly be described as planar ones.

Discussions of ligament-length changes in the literature (Mayfield *et al.*, 1976; Bonjean *et al.*, 1981; Taleisnik, 1985) were hitherto based on theoretical concepts of carpal kinematics, assuming planar carpal movements in the plane of hand motion around a fixed centre of rotation. For deviation Mayfield *et al.* (1976) thought the strips, which are called RadioLunate Palmar, LunateTriquetrum Palmar and TriquetroCapitate Palmar in the present study, would stabilize the movement of the hand to the radial side, while the opposite movement, ulnar deviation, was to be constrained by the RadioCapitate Palmar strip. As only strained ligaments are able to stabilize a movement, this means that during those movements these supposed stabilizing ligaments should be strained. Bonjean *et al.* (1981) suggested a similar straining pattern for carpal ligaments during deviation movements of the hand. Although Taleisnik (1985) expected out-of-plane movements of some carpal bones in radial and ulnar deviation, he came to the conclusion

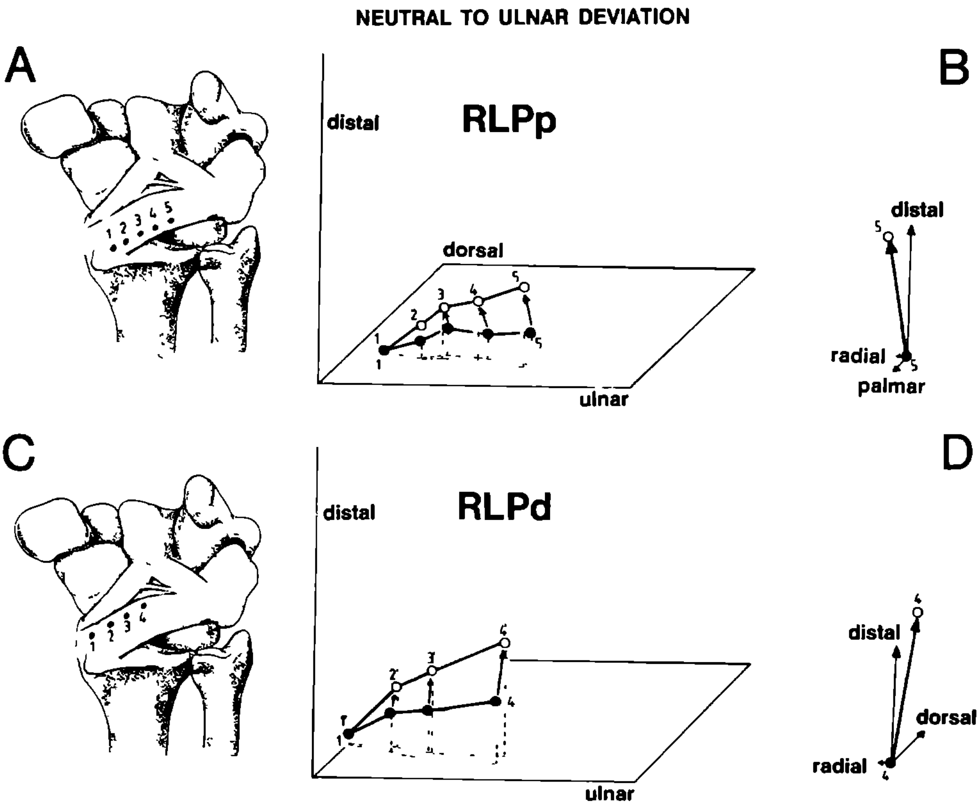


Figure 2.4. The 3D kinematics of the RLP ligament. The positions of the ligament markers and the 3D course of the RLP ligament are given.

A: The position of the RLPp ligament relative to the other carpal structures.

B: The positions of the RLPp ligament in the neutral position (•) and the ulnarly deviated position of the hand (○). The solid lines between the markers in a hand position show the interpolated course of the ligament, the arrows between two positions of a marker in different positions of the hand represent the motions of the markers due to ulnar deviation of the hand. The markers are numbered from proximal to distal in an increasing order. In the neutral position the markers are primeless, in ulnar deviation the markers are primed. The displacement of the most distal one (5→5'), is considered more in detail, its displacement vector is resolved in components along the main orientation axes, showing mainly palmar and distal displacement. This results in an approach of the insertion areas to each other.

C: The position of the RLPd ligament relative to the other carpal structures.

D: Similar to Figure 2.4B but now for the RLPd ligament in the neutral position and in ulnar deviation of the hand. The resolved vector for the displacement of the most distal marker (4→4') shows mainly dorsal and distal displacement. This results in an increase of the distance between origin and insertion.

that in radial deviation the RadioLunate Palmar and TriquetroCapitate Palmar strips will be strained. Our studies show that in maximal radial deviation none of the selected ligaments are strained relative to the neutral situation (Table 2.1). In maximal ulnar deviation, on the other hand, we showed that not only the RadioCapitate Palmar string is strained, as was predicted by Mayfield *et al.* (1976) and Bonjean *et al.* (1981) or the RadioLunate Palmar and TriquetroCapitate Palmar strings that Taleisnik (1985) considered to be lengthened, but that all three strings, RadioCapitate Palmar, RadioLunate Palmar and the proximal TriquetroCapitate Palmar string are strained (Table 2.1).

For flexion of the hand, dorsal as well as palmar, no such striking differences between speculations in the literature and the results of our experiments are evident. This is caused by the fact that in flexion smaller out-of-plane motions of the carpals occur, hence the motions are almost planar and because the ligamentous structures run almost perpendicular to the plane of movement. Hence, the ligament recruitment patterns are more trivial in this case, and less subtle.

Interaction of ligaments and carpals

In this study ligament lengths and carpal positions have been determined simultaneously in a number of flexion and deviation positions. Subsequently the ligament length changes and carpal motions for the motion steps between the positions of the hand have been calculated. It has been clarified how ligaments change in length with the changing positions of carpal bones: either insertion areas are displaced relative to each other, or the ligament course is influenced. It is shown that insight in the out-of-plane motion of the lunate is necessary to understand the behaviour of the RLP ligament. It has been explained why the distal string elongates, while at the same time the proximal one becomes shorter. The effect of the intervening scaphoid on the RCP ligament can only be understood when the 3D motion of the carpal bones and the 3D courses of the ligaments are considered.

STIFFNESS OF THE LIGAMENTS OF THE HUMAN WRIST JOINT [1]

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***ABSTRACT**-In the present study the stiffnesses of the superficial ligaments of fourteen human cadaver wrist-joints were determined. In these experiments fresh-frozen carpal joints were divided into a number of bone-ligament-bone complexes. These were loaded in a tensile testing machine and tested at a rate of 66% of the ligaments' initial length per second up to a maximal strain of 15%. From the force-elongation curves and ligament dimensions the tangent moduli for the ligament-bone strips were derived.*

The results show that, concerning the tangent modulus, there is not a clear differentiation among ligament strips. Only the dorsal Radio-Triquetrum ligament (RTD) and the palmar Radio-Capitate ligament (RCP) appear to consist of material of a relatively high tangent modulus, respectively about 93 and 83 MPa. The other seven ligaments tested have similar tangent moduli, ranging from 25 to about 50 MPa.

[1] Accepted for publication by *Journal of Biomechanics*, July 1991

INTRODUCTION

The explanation of the morphology of the carpal ligaments requires insight in their function. In the literature it is accepted that joint ligaments have mainly a kinetic function. They are supposed to transmit forces preventing luxation of a joint. Hence, to reach an explanation of ligament function, data on the forces in ligaments during movements of the hand relative to the forearm are needed. Since the carpal ligaments are relatively small, the forces which are developed during straining cannot accurately be determined using a direct measurement method. Therefore, these forces are derived indirectly in a sequence of pairs of relationships. The first relationship to be established is the one between ligament length and position of the hand relative to the forearm. Secondly, the relationship between ligament length and force has to be established. This relationship is dependent on the material characteristics. From these first two relationships a third one, the ligament-force pattern, *viz.* the relation between ligament force and position of the hand relative to the forearm, can be derived. It is the objective of this paper to describe the material characteristics of ligaments. Especially the length-force relationships of the superficial carpal ligaments, tested in a physiological range, will be addressed.

Logan and Nowak (1987), considering a number of the ligaments that we have studied too, give information on ultimate strains and ultimate forces of carpal ligaments. In another study Logan *et al.* (1986) report values characterizing the length-force relation of the deep scapholunate ligament, while we focus on the superficial ligaments. Mayfield *et al.* (1979) present data for two of the nine ligaments considered in this paper. The stiffness of the ligament, as well as its force-elongation pattern, is highly sensitive to its length and cross-sectional area. To obtain data that allow comparisons between intra-individual ligaments and between specimens, the tangent moduli of the ligaments are calculated.

METHOD

Material

Carpal ligament complexes of fourteen fresh-frozen human cadaver wrist joints were used (age: 63 - 78 years, average: 68.7 year). Eight of these originated from the left and right hands of four individuals. As far as known they did not have diseases which are known to influence collagenous tissue characteristics. Due to a slip of the scalpel or too much lengthening in the material testing machine, some of the ligaments were lost during the experiments. As a consequence, the n-values in the tables (Table 3.1A, 3.1B, 3.1C, 3.2A and 3.2B) do not always equal fourteen. The wrist joints were obtained from autopsy and kept frozen at -20 degrees Celsius until the time of use. It was shown that this procedure does not markedly affect the biomechanical properties of collagenous tissues (Viidik & Lewin, 1966; Matthews & Ellis, 1968; Noyes & Grood, 1976; Woo *et al.*, 1986). The duration of storage in frozen condition was maximally about six months.

Ligament identification

The complex carpal ligamentous interconnections of the wrist joint were macroscopically partitioned in strips with uniform fibre direction. Fibres that run parallel from one origin to the same insertion were supposed to belong to the same ligament. A total of seven ligament strips were distinguished, four on the palmar side, two on the dorsal side, and one on the radial side. As is common in the literature, the ligaments were named corresponding to their main origin and insertion sites respectively, further an uppercase P or D for palmar and dorsal is added to the ligament abbreviations (Mayfield *et al.*, 1976; Taleisnik, 1976, 1985). As for some wider ligaments a proximal and a distal part were tested separately, a lowercase 'p' or 'd' were added in order to differentiate between both parts. This notation has been introduced by De Lange *et al.* (1990c) and has been further elaborated by Savelberg *et al.* (1991). On the palmar side the RadioCapitate (RCP), RadioLunate (RLP), LunatoTriquetrum (LTP) and TriquetroCapitate (TCP) ligament were distinguished. On the dorsal side the RadioTriquetrum (RTD) and TriquetroTrapezium (TTD) ligament and radially the RadioScaphoid Collateral (RSC) ligament. Most of these ligament strips were described by Taleisnik (1976, 1985). However, more precise definition of the TTD and RSC ligaments may be necessary. The RSC ligament is the structure which is not unanimously considered a collateral ligament at the radial side (Kauer, 1980). It runs radially and distally from the RCP ligament from the dorsal-radial border of the radius to the radial side of the waist of the scaphoid. The TTD ligament on the dorsal side of the joint, also attaches to the distal border of the scaphoid in addition to its origin and insertion on the triquetrum and the trapezium. Further it has a number of extensions into trapezoid, capitate and lunate (Figure 3.1). In the experiments these small branches were not taken into consideration.

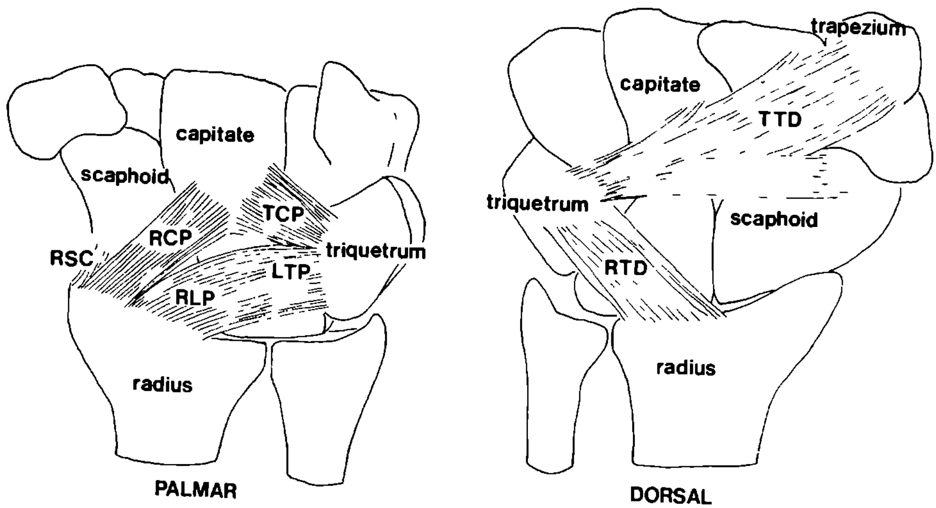


Figure 3.1 *The ligaments of the carpal joint (palmar view left, dorsal right).*

Specimen preparation

The frozen specimens were slowly thawed at room temperature. Following removal of the skin, the long flexor and extensor tendons and the connective tissue surrounding the carpal joint, the metacarpal bones and the greater proximal part of the radius were dissected. Using a reciprocating saw (Micro-aire, Valencia, California) the radius was then separated sagittally and frontally in parts comprising the origins of the ligament fibres to capitate (RCP), to lunate (RLP), to triquetrum (RTD) and to scaphoid (RSC). The triquetrum was separated frontally and transversally in parts comprising the origin of the ligaments to capitate (TCP) and to trapezium (TTD), and parts comprising the insertion of the ligaments from lunate (LTP) and from radius (RTD). Subsequently, the scaphoid was separated from its adjacent carpals. The few fibres which connect the RCP to the scaphoid and the RTD to the lunate are cut (Figure 3.2). To obtain ligament fascicles as small as possible, so that the effect of bad alignment during the tensile tests would be as small as possible, and so that different parts of a ligament strip could be tested separately, the wider ligament strips were split. Therefore, the RTP complexes, which consist of a part of the radius, the RLP ligament, the lunate, the LTP ligament and a part of the triquetrum (Figure 3.2), were divided evenly in half in all specimens along the fibre directions of the ligaments in a proximal and a distal part. The RTD ligament and its radial attachment sites were split in six specimens. The RCP ligaments were wide enough in three specimens to justify the division into a proximal and a distal string. The following bone-**ligament**-bone complexes (BLB) were created (Figure 3.2):

* Radius - **RLP** - Lunate - **LTP** - Triquetrum.
* Radius - **RCP** - Capitate - **TCP** - Triquetrum.
* Radius - **RSC** - Scaphoid.
* Radius - **RTD** - Triquetrum.
* Triquetrum - **TTD** - Trapezium.

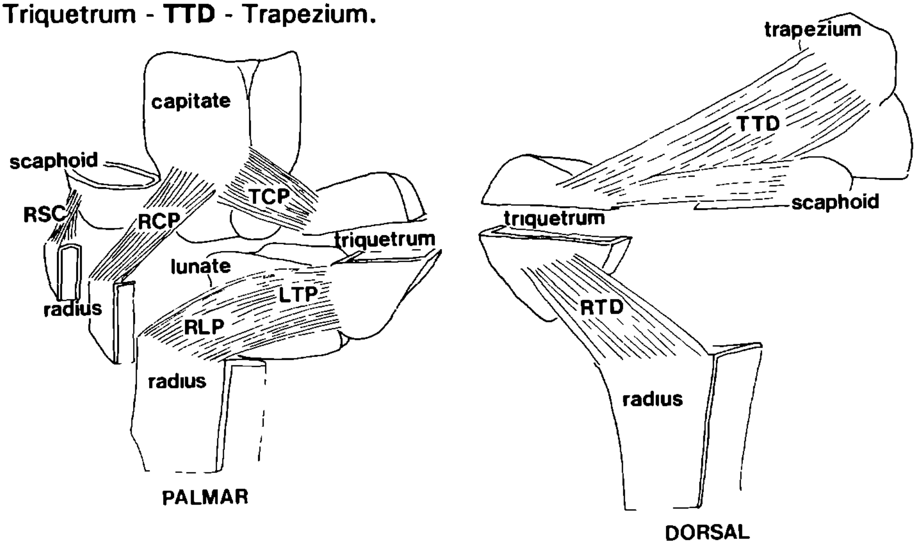


Figure 3.2 *The bone-ligament-bone complexes which were isolated from a carpal joint.*

The RCP and TCP ligaments were tested by fixing the radius and the capitate or the triquetrum and the capitate, respectively, in the testing machine. For practical reasons this procedure could not be followed to test the fascicles of RLP and LTP ligaments separately. This complex of bony parts and ligaments was first tested with the radius and triquetrum fixed in the testing machine. Hence, the RLP and LTP were connected in series in this test. This test and its results are referred to by the abbreviation RTPp or RTPd. Subsequently the LTP ligament and the triquetrum part, to which it was connected, were dissected and the RLP ligament was tested separately by clamping the radius part and the lunate. The differences between the RLP and RTP measurements give insight in the properties of the LTP ligament.

After all the bone-ligament-bone complexes were divided into their final parts, the bony parts were embedded in acrylic cement to provide a better grip in the material testing machine (Butler *et al.*, 1986). These polymethylmethacrylate-units are fixed by screws in small containers, which can be connected to the material testing machine (MTS, Berlin, Germany). On one side they are fixed by a ball and socket joint to the beam of the testing machine and on the other side by a load cell (MTS, Berlin, Germany), which can record forces up to 100 N. By means of the ball and socket joint, and the possibility to move the other container in the plane perpendicular to the line of applied force, both the containers can be situated relative to each other so that the displacement direction of the machine is parallel to the main direction of the fibres of the ligament tested.

Testing procedure

The specimens were visually positioned in the testing machine in a way that most of the fibres appeared to be parallel to the displacement-direction. To control this *a posteriori*, three different sessions of tensile testing were conducted. The stiffest of these sessions was supposed to represent the most proper fixation of the specimen to the testing machine. The data of this session were used for further processing. Between the sessions the specimens were given enough time to recover, so that the data taken from different sessions are fully comparable to each other. The time that elapsed between thawing and the last cyclic loading session was maximally three days. On the first day after thawing the wrist joint was divided in bone-ligament-bone specimens, the second and third day after thawing were used for the material testing. Between the testing session the ligaments were wrapped tightly in Ringers-solution-soaked paper tissues, and were stored in a refrigerator.

To precondition a ligament, it was subjected to at least 16 load cycles during a test. The data of the five last cycles were used for analysis. The load cycles were conducted at a rate of 66% of the initial length per second to a maximal displacement of 15% of the initial length. This corresponds to an absolute displacement ranging from 1.2 to 6 mm and an absolute rate ranging from 5 to 25 mm/s. Noyes *et al.* (1974) showed that the recorded stiffness of a ligament depends on the strain rate, but only when changed by a factor of 100 or more. The relative strain rate chosen here is similar to the one chosen by Noyes *et al.* (1974). This rate is close to the physiologically normal, which is about 100 %/sec (Butler *et al.*, 1978). From a pilot study it appeared that elongating the tissue to 15% of its initial length is, on the one hand required to reach the linear part of the force-elongation curve, and on the other hand low enough not to inflict irreversible damage upon the carpal ligaments. Logan and Nowak (1987) report the onset of permanent deformation to occur for strains of 18.4% for the RCP ligament and 32.4% for the RLP-ligament. Mayfield *et al.* (1979) find for both ligaments that the failure strain was about 20%. For other, deeper ligaments even higher maximal strains have been reported (Logan & Nowak, 1987).

During a test, the forces were measured by a load cell, sampled at a rate of 200 Hz and subsequently stored in a personal computer. During preparation and tensile testing, the specimens were moistened by a Ringers solution. The temperature of this solution equalled the room temperature, which was not explicitly controlled, but was about 22 degrees Celsius.

Determination of ligament length and cross-sectional area

The initial length of the ligaments (l_0) was determined by a vernier callipers. In the literature a number of methods for the determination of the ligament cross-sectional area are discussed (Allard *et al.*, 1979; Ellis, 1969; Lee & Woo, 1988; Butler *et al.*, 1984). In this study an area-micrometer with matching pairs of jaws was used (Allard *et al.*, 1979; Butler *et al.*, 1984) (Mitutoyo, Tokyo, Japan). The main reasons for this approach are the easy applicability and good reproducibility (Ellis, 1969; Butler *et al.*, 1984). Depending on the dimensions of the ligament, two jaw sizes could be chosen. The pressure between the micrometer parts was 0.44 or 0.15 MPa, for the smaller and the larger pair of jaws, respectively. When a ligament fits the smaller as well as the larger pair of jaws, the data of the smaller pair were omitted. Because due to the smaller pressure between the parts, when the larger pair of jaws is used, the ligament will be subjected to less deformation. From a study of Allard *et al.* (1979) on knee joint ligaments it appears that increasing interjaw pressure to values higher than about 0.15 MPa did not affect the cross-sectional area measured. In a few cases a BLB preparation of the rather short TCP ligament did not fit into the area-micrometer. In that case the cross-sectional area was estimated by means of the vernier callipers. The cross-sectional areas of the LTP ligaments were not measured in any of the specimens; their lengths are too small to fit into the area-micrometer. These cross-sectional areas were assumed to equal those of the corresponding RLP ligaments. The LTP ligament seems roughly to be as wide as the RLP ligament. For the determination of all these width and length parameters the means and standard deviations of at least three measurements were calculated.

To check the accuracy of the determination of ligament lengths and their cross-sectional areas the ligament parts of one specimen were measured several times on different days, before and after the material testing. Also the effect of the pressure between the micrometer parts was considered, therefore some ligaments that fitted both sizes of pairs of jaws were measured in both the small (0.44 MPa) and the large jaws (0.15 MPa).

Data processing

From the tensile tests the stiffness (K) of a ligament in the steepest, linear part of the force-elongation curves was determined by means of linear regression analysis. To compensate for random noise the values for the stiffnesses of the five last cycles of a session (Figure 3.3A) were averaged. This mean value was considered the stiffness of that session. To calculate the tangent modulus for the linear part of the force-elongation curve a modified reference length l_{ref} must be determined. This reference length, which is larger than the initial length l_0 measured, is corrected for the non-linear part of the force-elongation curve (Figure 3.3B), and calculated according to:

$$l_{ref} = l_0 + \Delta l - \left(\frac{F_{max}}{K}\right) \qquad (3.1)$$

where l_0 is the initial length as determined by the callipers (mm), Δl is the applied lengthening in the tensile machine (mm), F_{max} is the mean of the recorded maximal forces of the last five load cycles (N), and K is the linear stiffness (N/mm).

The tangent or Young's modulus can be calculated according to the following equation adapted from Butler *et al.* (1978):

$$E = \frac{K \times l_{ref}}{A_0} \qquad (3.2)$$

where E is the tangent modulus (MPa), l_{ref} is the reference length (mm), and A_0 is the reference cross-section (mm^2).

To test the significance of the differences in tangent moduli of the ligaments, the nonparametric Walsh-test (Siegel, 1956) is used. In respectively only three and six specimens, the RCP and RTD ligaments are divided in a proximal and a distal string. As for the RCP ligament the separation of this ligament from other carpal collagenous structures is most clear on the proximal border, and for the RTD ligament the distal border can most easily be marked, the values for respectively the proximal and the distal strings of the RCP and RTD ligament are considered to represent the forces, stiffnesses and tangent moduli of the ligaments in these specimens.

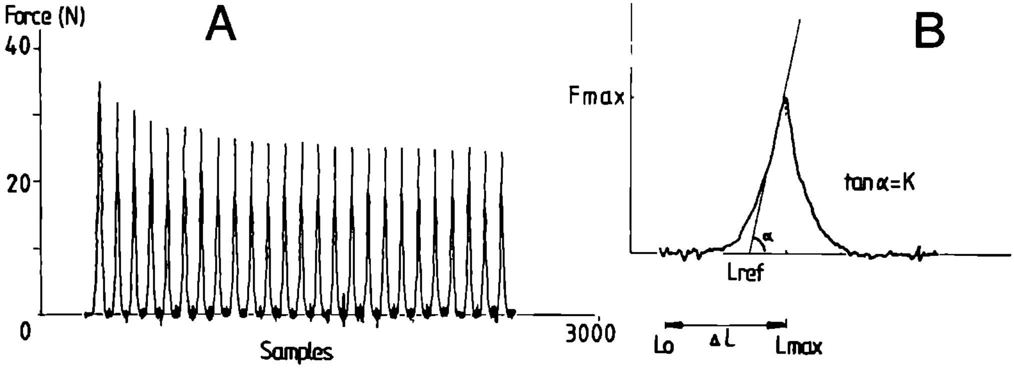


Figure 3.3 A: A typical force-registration of a tensile-test of a carpal ligament, showing the levelling off of the peaks of the subsequent loadings.
B: A typical force-elongation curve for a preconditioned carpal ligament, showing the delay of force development, the toe-region and the linear part of the curve. Furthermore, the calculation of l_{ref} is illustrated.

RESULTS

The average initial lengths for the ligaments tested range from 2.7 mm (LTPp) to 40.9 mm (TTD) (Table 3.1A). The average cross-sectional areas of the ligaments vary between 6.0 mm^2 and 18.4 mm^2 (Table 3.1B). If the ligament was divided in two strips, the measurements for the proximal and distal parts of a ligament are summed and the total cross-sectional areas of the ligaments are presented. No significant (*t*-test, $p<0.05$) differences are found between repeated measurements on different days for ligament length and for cross-sectional area. It is concluded that these determinations are accurate enough. Significant (*t*-test, $p<0.05$) differences are found for the cross-sectional area measurements using two different sizes of pairs of jaws. On the average, the smaller pair of jaws result into 7.1% lower values for the cross-sectional area than the larger ones.

A representative example of a force-registration graph is shown in Figure 3.3A. It can be noticed that after about ten load cycles the ligament preparation reaches its preconditioned state. The decrease of the maximum registered forces for subsequent cycles is neglegible. Furthermore, if we consider this force-registration curve more in detail and look at the individual peaks, we see in Figure 3.3B a representative profile of the force-strain curve.

Table 3.1 A: The initial ligament lengths (mm), averages, standard deviations, and the number of specimens.
B: The ligament cross-sectional areas (mm^2), averages, standard deviations, and the number of specimens.

	INITIAL LIGAMENT LENGTH		
	mean	sd	n
RSC	9.9	2.0	7
RCPp	28.6	5.2	3
RCPd	24.3	6.9	3
RCP	27.1	2.6	10
RLPp	11.2	2.2	14
RLPd	12.5	2.5	14
LTPp	2.7	1.4	9
LTPd	4.7	1.0	10
TCP	11.4	1.5	14
RTDp	15.0	2.0	7
RTDd	18.0	1.8	7
RTD	16.7	2.5	7
TTD	40.9	6.6	14

	CROSS SECTIONAL AREA		
	mean	sd	n
RSC	6.0	3.1	7
RCP	11.9	3.5	3
RLP	18.4	8.2	3
TCP	16.1	4.1	14
RTD	13.1	5.4	14
TTD	11.9	3.8	13

The averaged forces, which were recorded when preconditioned ligaments were strained 15%, range from 6.9 N (RSC) to 44.4 N (RTDd) (Table 3.2A). The stiffnesses that were calculated for these ligaments have values between 10 N/mm for the RSC and 46.6 N/mm for the RTDd ligament (Table 3.2B). The tangent moduli vary between 22.6 MPa (RSC) and 119.3 MPa (RTDd) (Table 3.2C).

To check for trends in the differences between the moduli of the ligaments, the levels of significance of the Walsh-test are presented in Table 3.3. The tangent moduli of the RTD and the RCP ligament are significantly higher than the moduli of all other ligament preparations tested. The difference between these two ligaments themselves is not significant. When tested mutually, most of the differences between the other ligaments (RSC, RLPp, RLPd, RTPp, RTPd, TCP and TTD) are not significant. Only in five cases the differences between the ligaments are significant: the RLPd ligament has a significantly higher tangent modulus than the RSC and the RTPp ligaments; the RTPd ligament consists of significantly stiffer material than the RTPp and the TCP ligaments; the TTD ligament has a significantly

Table 3.2 *The forces (N) registered when the ligaments were strained 15%, the calculated ligament stiffnesses (N/mm) and the tangent moduli (MPa), averages, standard deviations, and the number of specimens. The single asterisk (*) denotes the average value of the 3 proximal strings of the RCPp (when tested separately) and the 10 undivided RCP ligaments. The double asterisk (**) denotes the average value of the 6 distal strings of the RTDd (when tested separately) and the 7 undivided RTD ligaments.*

	FORCE (N)		STIFFNESS (N/mm)		TANGENT MODULUS (MPa)		
	mean	s.d.	mean	s.d.	mean	s.d.	n
RSC	6.9	5.2	10.0	7.6	22.6	18.1	7
RCPp	17.4	2.8	19.3	13.0	102.3	38.0	3
RCPd	31.0	22.5	23.9	16.6	67.4	33.1	3
RCP*	36.0	14.3	27.2	10.8	83.0	34.1	14
RTPp	13.6	9.8	15.6	9.0	26.9	21.1	11
RTPd	19.0	12.8	18.6	10.0	51.2	33.1	11
RLPp	24.5	14.4	32.7	20.2	42.5	19.4	14
RLPd	19.5	12.1	26.7	18.0	49.5	27.7	14
TCP	24.0	11.4	35.6	17.4	28.9	20.8	14
RTDp	23.7	11.8	24.9	11.6	67.9	37.5	6
RTDd	44.4	26.4	46.4	24.0	119.3	31.4	6
RTD**	43.7	20.8	44.4	20.9	93.1	56.6	13
TTD	23.3	13.2	14.2	6.1	47.5	25.1	12

higher tangent modulus than the RTPp ligament. Despite these five significant differences, the differences between the mean tangent values of these ligaments (RSC, RLPp, RLPd, RTPp, RTPd, TCP and TTD) are small enough to consider them all as one group.

Significant differences between the proximal and the distal strings of the RTD (n = 6) and the RTP ligament (n = 11) are found. The proximal and distal strings of the RLP ligament (n = 14) are not significantly different concerning the tangent modulus. For all three ligaments it appears that the tangent moduli for the proximal strings are lower than those for the distal parts. The number of specimens for which the RCP ligament is tested in separated parts, proximally and distally, is too small (three values) to allow for a statistical test. Finally, when comparing the tangent moduli for the RTP and the RLP strips, where the second one is a part of the first one, it is established that the tangent moduli for both testing configurations do not differ significantly. This means for the tangent moduli of the LTP parts, that they will have magnitudes similar to those of the corresponding RTP and RLP parts, assuming that the cross-sectional areas are similar to those of the RLP.

We conclude that the superficial ligaments of the wrist-joint ligaments can be divided in roughly two groups (Figure 3.4). The ligaments of the first group, containing the RTD and the RCP ligaments, have the highest tangent moduli of about 80 to 90 MPa. The ligaments in the second group, the RSC, RLPp, RLPd, RTPp, RTPd, TCP and TTD ligament, have values for the tangent moduli ranging between approximately 25 to 50 MPa.

Table 3.3 The level of significance for the differences in tangent moduli between the tested ligaments, 'ns' denotes that the ligaments do not differ significantly.

	RCP	RLPp	RLPd	RTPp	RTPd	TCP	RTD	TTD
RSC	<0.016	ns	<0.016	ns	ns	ns	<0.016	ns
RCP		<0.005	<0.005	<0.005	<0.005	<0.005	ns	<0.011
RLPp			ns	ns	ns	ns	<0.005	ns
RLPd				<0.028	ns	ns	<0.01	ns
RTPp					<0.011	ns	<0.005	<0.051
RTPd						<0.005	<0.025	ns
TCP							<0.005	ns
RTD								<0.005

DISCUSSION

Mayfield *et al.* (1979) presented data for the RCP and the RTP ligament that are similar to the data presented here. For the ligament which they called RC (similar to the RCP), they reported an tangent modulus of about 65 MPa; for the VRT ligament (similar to the RTP) they found about 80 MPa. They did not test the other superficial ligaments. Considering these two ligaments the results are similar. Logan *et al.* (1986), and Logan and Nowak (1987) determined material characteristics for extrinsic as well as intrinsic ligaments, they considered patterns of stress relaxation and maximal stresses and strains. For the ligaments they tested, they did not determine the tangent modulus for the linear part of the force-elongation curve of a ligament, hence comparison with the results of the present study is impossible.

There are a number of factors that influence our data and some remarks have to be made on tested material and testing method.

Firstly, it should be mentioned that the data, as presented in Figure 3.4, are based on averages from high aged donors (n = 14, range: 63 - 78 years, average 68.7 years). As far as could be checked, they did not have diseases that are known to influence material characteristics. But for knee-joint ligaments, aging has been shown to have a decreasing effect on tangent moduli (Noyes & Grood, 1976; Butler *et al.*, 1978). Wang *et al.* (1990) did not find an effect of age on the tangent modulus in canine medial collateral ligaments. On the other hand Viidik (1973), in a review-article, cited studies that show decrease and others that show increase of tangent modulus with aging. This supported his statement that aging is a change very difficult to define.

TANGENT MODULUS (MPa)

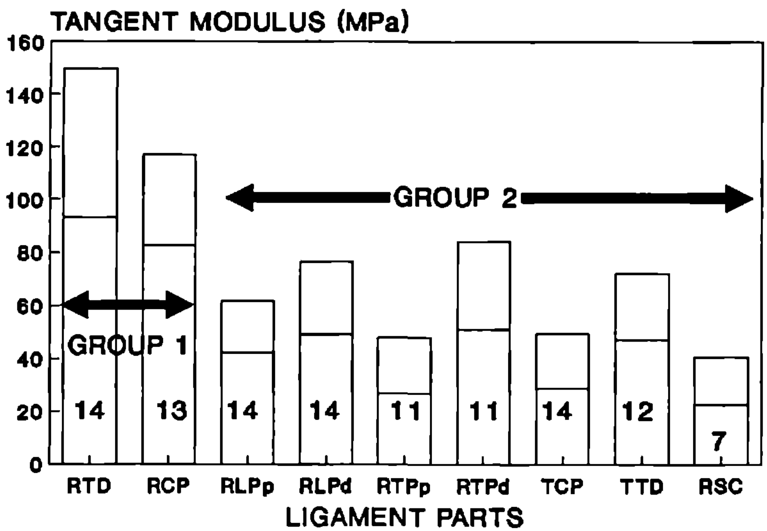


Figure 3.4 The mean tangent moduli for each ligament in MPa and their standard deviations. The numbers in the columns denote the number of specimens which are studied for that ligament. The groups denote the ligaments that can be considered to have a similar tangent modulus.

Secondly, the tangent modulus is calculated, using results on initial length, cross-sectional area and stiffness (see Method section). Therefore, the reliability of the determination of the tangent modulus depends on the accuracy with which the initial length, the cross-sectional area and the stiffness can be determined. Tests show that the length of the ligaments and cross-sectional area measurements can be reproduced satisfactorily. The error introduced by using different pairs of jaws is only minor. We conclude that the initial lengths of the ligaments and cross-sectional areas are determined reliably. The reliability of the stiffness determination depends on two factors. First the alignment of the ligament in the tensile testing machine has an effect on the measured force. We ensured testing the most proper alignment by testing the ligaments three times. Before each test the ligament was visually aligned in the most proper way, independent of the foregoing test(s). Only the test with the highest force was taken into account. The determination of the linear part of the force-elongation output is the other factor influencing the stiffness reliability. We ensured that only data-points of the linear part of the force-elongation curve are used to calculate the stiffness.

It is found that different parts of ligaments, proximal and distal ones, can have different tangent moduli. It should be questioned if these differences are due to the design-specifications set for the carpal joint, or if they are introduced by experimental errors. The possibility that these differences have to be ascribed to experimental errors cannot be ruled out. As was mentioned in the methods section the demarkation of some of the ligaments is not always as easy as would be desirable. The proximal borders of the RTD, the RLP and the RTP ligaments are less easily to define than their distal borders, for the RCP ligaments the distal borders are hardest to define correctly. It appears that in the cases that differences were found between the proximal and the distal parts of ligaments (RTP, RTD), especially those strings which have a less easily defined border have the lower values for the tangent moduli. Hence, there is a strong suggestion that these kinds of differences are caused by preparation artifacts, and that a ligament has only one tangent modulus and not different moduli for different strings. As the experimental design was not set up to discover these differences it is not possible *a posteriori* to check if they are really artifacts or if they concern differences imposed by the design-specifications of the wrist joint.

Comparing the presented data on tangent moduli to those of ligaments in other human joints is rather difficult, since in the various studies a wide variety of experimental set-ups has been used, and since the strain rate applied in tensile tests is of great influence on the results (Noyes *et al.*, 1974). However, when comparing this study with a study with a similar strain rate on human knee-joint ligaments (Butler *et al.*, 1986), it becomes clear that the values for the tangent moduli differ highly. The values presented by Butler *et al.* (1986) are about 4 to 7 times higher than those presented in this paper. So, wrist-joint ligaments show relatively low tangent moduli with only relatively small differences between the individual ligaments.

This kind of data does not allow a functional explanation of the difference found, therefore insight in ligament forces is required. The importance of these data is in its documentation for the carpal joint, which had not been done before.

In conclusion, it can be said that carpal ligaments have similar tangent moduli, although two of the ligaments considered appear to consist of significantly stiffer material. When compared to the human knee joint ligaments the tangent moduli of the carpal ligaments are much lower.

EFFECTS OF PRECONDITIONING ON WRIST-LIGAMENT FORCES; ESTIMATES WITH AN INDIRECT MEASUREMENT METHOD FOR JOINT SPECIMENS [1]

H.H.C.M. SAVELBERG, J.G.M. KOOLOOS, R. HUISKES and J.M.G. KAUER

***ABSTRACT-A** method has been developed to calculate the forces that are developed in the ligaments of a joint specimen during motions. This indirect method is needed since direct measurements fail in the case of small ligaments. As an example the small ligaments of the carpal joint are considered. The rationale of the method is that the force generated in a ligament depends on the amount of strain to which it is subjected and on its material characteristics. In the method presented the lengths of the ligaments are determined in vitro at several joint positions by means of Röntgenstereophotogrammetry. The zero-force length and the force-elongation relationship are determined on the same ligaments isolated in a materials testing machine.*

The method is reasonably accurate. Over a considerable part of the strain range the measurement errors, which are estimated from the accuracies in the different steps of the method, are relatively small when compared to the forces determined. The method is very well applicable to joints in situations where other measuring methods fail. The present analysis shows, however, that the force values determined are very susceptible to preconditioning of the ligaments. This indicates, that ligament forces may vary considerably in vivo, depending on the extent of preconditioning provoked by a particular function.

[1] Submitted for publication.

INTRODUCTION

The *in vitro* measurements of ligament forces are subject to a number of problems. In many joints the ligaments are small and not easily accessible for relatively large measuring devices, *e.g.* buckle transducers. The main problems with these devices are impingement with the bones and ligament shortening due to the installation of the device. Although the design of buckle-type transducers has been improved several times (Lewis *et al.*, 1982; Barry and Ahmed, 1986; An *et al.*, 1990), the interference with the surrounding structures remains a problem for small joints, such as the wrist. The same can be said for a recently developed method, which uses a small implantable force transducer (Xu *et al.*, 1990; Cummings *et al.*, 1991). Takai *et al.* (1991) determined knee-ligament forces individually, based on kinematic data obtained from the intact joint and load-elongation data, determined after dissection. In this way the application of mechanical devices to the knee-joint ligaments is avoided.

We have developed a similar method of indirect, non-invasive measurement, and applied it to the ligaments of the carpal joint. Firstly, the elongation in a ligament during a motion of the wrist joint is determined and subsequently the relationship between force and elongation for that ligament is established. As a result, the force generated in the ligament during the motion studied is calculated. The elongation is determined *in vitro* by Röntgenstereophotogrammetric analysis (RSA; Selvik, 1974; 1989), which can be assumed not to influence the behaviour of the ligaments or the carpal bones. The force-strain relationship, including the zero-force or unloaded length, is determined from isolated ligament preparations in a tensile testing machine.

Viidik (1973; 1980) showed that due to repeated loading the laxity of ligaments increases. This also implies that the unloaded length increases. After a few loading cycles this process stabilizes. Hence, to obtain reproducible and interindividually comparable force-elongation curves, it is necessary in material testing procedures to precondition the ligaments (Fung, 1972; Viidik, 1973; Butler *et al.*, 1978; Woo *et al.*, 1983, 1986).

The present paper explains the method as it is applied to ligaments of a wrist joint, and reports on the accuracy of the method and on the effects of preconditioning on the forces estimated.

METHODS

The method to estimate ligament force patterns consists of three stages: (i) the determination of ligament length in several positions of the joint, (ii) the determination of the zero-force length of the ligament, and (iii) the recording of the force-elongation relationships for the ligaments.

Determination of the in vitro ligament length

In this study the Röntgenstereophotogrammetric analysis (RSA) method to determine the three dimensional position of markers (Selvik, 1974; 1989) is used. This method has been further developed by de Lange *et al.* (1990c) to enable the measurements of ligament length and ligament-length changes in the wrist joint. Ligaments are provided with one or two strings of radio-opaque markers (tantalum pellets). The ligament length is represented by the summation of subsequent marker intervals. In the present study, four superficial ligaments (RCP, RLP, TCP and RTD) of a wrist-joint specimen are provided with pellets (de Lange *et al.*, 1990c;d Savelberg *et al.*, 1991). The RLP ligament, which is a relatively wide ligament, is marked with two strings of pellets, a proximal (RLPp) and a distal one (RLPd). After this preparation the specimen is positioned into a motion constraining device (de Lange *et al.*, 1985) in which the flexion or deviation angle between the hand and the forearm can be controlled. At different deviation and flexion angles, pairs of stereo radiographs are made. For flexion the so-called neutral hand position, and the positions at 10 or 15 degree intervals from the neutral position are selected (10, 20, 35, 50, 65 and 84 degrees to both palmar and dorsal flexion). For deviation the neutral position is selected too, as well as positions at 10 degree intervals towards ulnar and radial deviation (10, 20, 30, 40, 50 and 60 degrees ulnar deviation and 10, 20, 30 degrees radial deviation). The positions at 84 degrees dorsal and palmar flexion and at 60 degrees ulnar deviation and 30 degrees radial deviation represent the maximal excursions of the joint. Form the stereo radiographs the three-dimensional position of the markers can be reconstructed and the ligament lengths (L) can be calculated at each position of the joint (de Lange *et al.*, 1990c; Savelberg *et al.*, 1991).

Determination of the zero-force length and the force-elongation relationship of the ligaments

After the *in vitro* RSA experiments, the specimens are partitioned in bone-ligament-bone (BLB) preparations (Savelberg *et al.* (submitted)). Each

BLB-preparation corresponds to one of the ligaments or ligament parts marked and considered in the *in vitro* RSA-experiment. The isolated ligaments and the bony parts still contain the markers which are provided to them for the *in vitro* RSA-experiments.

The BLB-preparations are then placed in a slack position in a tensile testing machine. The ligament fibres are aligned with the load axis of the testing machine as good as possible.

From the slack position the ligament is elongated until it starts to generate a small amount of force (0.25 N). This is detected by a load cell (MTS, Berlin, Germany) to which one of the bony parts of the BLB-specimen is connected. An additional pair of stereo radiographs is made in this position. From this pair of radiographs the zero-force length of the ligament (L_{ZF}) is calculated.

Immediately after the stereo radiographs for the zero-force length determinations have been made, the ligaments are subjected to cyclic tensile tests. In the tensile testing machine the BLB-preparations are stretched 25 times to 15 percent of their initial lengths at a rate of 66 percent/sec of the initial lengths. For this purpose, the initial length is determined by a pair of vernier callipers before the ligament is positioned in the tensile testing machine. During the tensile test the ligament force, registered by the load cell, is sampled at a rate of 200 Hz and stored in a personal computer.

Because the ligament alignment procedure performed before testing begins can only be controlled visually, hence is not very precise, it is repeated three times. Each time the full testing procedure is performed. The test resulting in the highest stiffness characteristics of the three is then chosen for further processing. Between each of these three tests, a period of at least half an hour is applied, to allow the ligament to recover.

Data processing

A second degree polynomial equation is fitted to the force-elongation data points of the first loading cycle, when the ligaments are not preconditioned. A similar polynomial equation is calculated for the data points of the last five loading cycles, when the ligaments are preconditioned. The polynomial equation is of the form

$$F = aL^2 + bL + c, \qquad (4.1)$$

where a, b and c are constants, F is the force (N) developed in the ligament and L is the elongation of the ligament (mm).

When the ligament is preconditioned, the force development first starts after the ligament has been strained for some percents; hence, the force-elongation curve has shifted to the right. This implies, that also its zero-force length has increased somewhat. The preconditioned zero-force length is then estimated from the force-elongation measurement sampling points, taking the first point of which the force is greater than zero as the zero-force length. This value is less well defined as the one determined in the procedure for the first loading cycle. However, it was shown that small variations hardly affected the constants in the polynomial fit.

To calculate the forces that a ligament generates in a position p of the hand (F(p)), the effective elongation (EL(p)) in that position is calculated according to

$$EL(p) = L(p) - L_{ZF}, \qquad (4.2)$$

where L(p) is the *in vitro* length of the ligament determined in the RSA-experiment, with the hand in position p, and L_{ZF} is the zero-force length of the ligament. By substituting the value of EL(p) for L into the quadratic polynomial equation (4.1) the force developed by the ligament in that given position of the hand is calculated. The forces are plotted against the position of the hand, giving ligament force patterns.

Accuracy of the method

The accuracy of this method for estimating the force developed in a ligament may be affected by several factors, including the precision of the determination of the *in vitro* ligament length, the precision of the measurement of the zero-force length, and the fit of the quadratic polynomial equation.

The accuracy of the *in vitro* ligament length, measured in the RSA-experiment, depends on the accuracy of the RSA-method, *i.e.* the precision of the 3D reconstruction of the markers. Savelberg *et al.* (1991) found that the standard deviation for the determination of carpal ligament lengths with 4 or 5 markers ranged between 0.005 and 0.055 mm. This standard deviation will be referred to in this paper by σL.

The variations in the zero-force length measurement can be also attributed to errors in the 3D reconstruction of the markers. Hence the standard deviation for the zero-force length determination (σL_{ZF}) equals that for the *in vitro* ligament length measurement (σL).

The standard deviation of the effective elongation (σEL) is calculated according to

$$\sigma EL = (\sigma L^2 + \sigma L_{2F}^2)^{1/2} \qquad (4.3)$$

The accuracy of the force-elongation relationship (r^2), which is represented by the second degree polynomial equation, is calculated by a sum of squares approach for the differences between the sampled force measurements and the forces calculated by the polynomial equation, according to:

$$r^2 = \frac{1}{n} \sum_{i=1}^{n} (F_i(EL) - \hat{F}_i(EL))^2 \qquad (4.4)$$

where $F_i(EL)$ is the force calculated by the polynomial equation for a given *effective elongation (EL), $\hat{F}_i(EL)$ is the force measured in the tensile testing* machine at the same effective elongation (EL), and n is the number of force samples to which the quadratic polynomial equation is fitted. Hence this value r^2 gives the amount of variance of the force, which cannot be explained by the polynomial equation. It is inversely proportional to the goodness of the fit.

The standard deviation for the force calculated at a certain position of the hand (σF) can be obtained from

$$\sigma F(p) = (\sigma EL^2[2aEL(p) + b]^2 + r^2)^{1/2} \qquad (4.5)$$

where $\sigma F(p)$ is the standard deviation of the force developed by a ligament with the hand in position p, σEL is the standard deviation for the calculation of the effective elongation of the ligament, a and b are the constants of the quadratic polynomial equation describing the force-elongation relationship, EL(p) is the effective elongation of the ligament at position p of the hand, and r^2 is the sum-of-squares approach representing the goodness of fit of the quadratic polynomial equation to the force samples.

RESULTS

Accuracy

For the case that the alignment error in the determination of L is neglected, the value for σL is considered to be 0.055 mm, as indicated in the previous section. This value is the upper level for this error as reported by Savelberg *et al.* (1991). The error made in the determination of the zero-force length is also assumed to be 0.055 mm. Consequently, the accuracy for the effective elongation computation (σEL) is 0.078 mm. The standard deviations for the force determinations (σF_{max}) at the maximally applied strain in the material testing machine vary between approximately 2 N and 5 N (Table 4.1). The forces which are calculated at these 'maximal' strains range from 39 N to 115 N. In Figure 4.1 A-E the quadratic polynomial equations for the effective-lengthening force relationships for each ligament or ligament part and their standard deviations are presented.

Table 4.1 *The ligament lengths in the neutral position of the hand ($L_{NEUTRAL}$), the zero-force length (L_{ZF}) and the forces generated by the ligaments when maximally strained in the tensile testing machine (F_{max}), and the standard deviations for the effective length determinations, σEL for the ligaments tested. Furthermore the value for r^2, the fit of the quadratic polynomial equation to the force-samples. σF_{max} gives the standard deviation for the force calculation when the maximal elongation in the tensile testing machine is applied.*

	$L_{NEUTRAL}$ (mm)	L_{ZF} (mm)	σEL (mm)	r^2 (N^2)	F_{max} (N)	σF_{max} (N)
RCP	31.94	36.92	0.078	1.18	115.4	4.3
RLPp	18.20	17.14	0.078	0.56	58.6	5.2
RLPd	16.12	15.61	0.078	1.13	43.4	3.8
TCP	18.18	16.48	0.078	0.74	92.2	6.3
RTD	21.15	19.66	0.078	0.07	39.2	2.3

Contribution of different errors to final σF

The error in the estimate of the ligament forces is the accumulation of two constant experimental errors: the error in the determination of the effective elongation (σEL) and the error in the fit of the polynomial equation to the force-elongation data points (r^2). The contribution of σEl depends furthermore on the current stiffness (the derivative of the quadratic polynomial equation at a given elongation) of the ligament. The contribution of the r^2-values to the final σF is small, maximally about 1.2 N^2 (Table 4.1). In

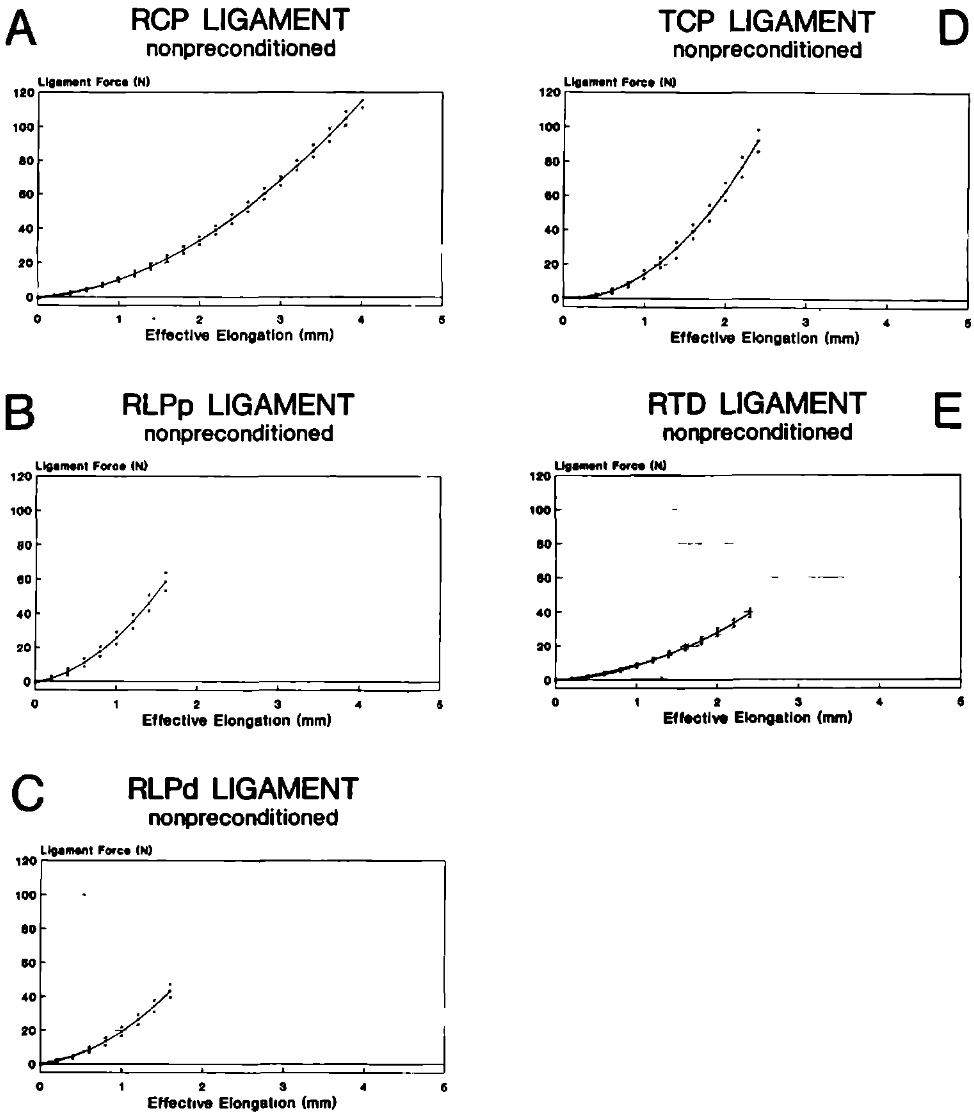


Figure 4.1 *The forces calculated for a range of effective-elongations by the quadratic polynomial equations, and their standard deviations for the five ligaments tested: RCP (A), RLPp (B), RLPd (C), TCP (D) and RTD (E). The effective-elongation ranges resemble the ones that were applied in the material testing machine. The standard deviations, σL, are given as dotted lines.*

Figure 4.2 the force samples and the calculated second degree polynomial equation for the RCP-ligament are plotted to show the fit corresponding to the data points determined. Especially when the effective elongation increases, the relative contribution of r^2 to σF in equation (4.5) is of minor importance. The contribution of the error in the determination of the effective elongation is also of minor importance; for wrist-joint ligaments it is determined to be approximately 0.078 mm. The main influence on the error in the force determination originates from the effective elongation. When the effective elongation increases, the current stiffness of the ligament, in equation (4.5) the component {2aEL(p) + b}, is enlarged, and this results in a higher inaccuracy of the force determination.

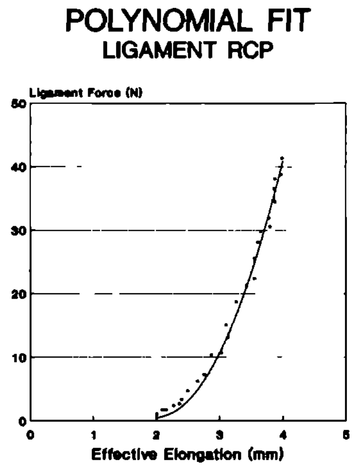


Figure 4.2 The quadratic polynomial equations calculated for the effective-elongation force relationships of ligament RCP, and the measured force-samples.

Effect of preconditioning on the estimated ligament forces

Due to preconditioning the estimated forces in the ligaments decrease (Figure 4.3 A-E). This decrease of force is accompanied by an increase of the zero-force length in the preconditioned ligament. Hence, a ligament first starts to generate forces at higher elongation levels. For the ligaments tested the increases of the zero-force lengths range between 0.9 and 5.4 percent of the zero-force length as determined in the non-preconditioned ligament. Depending on the effective elongation of a ligament during the movements applied to the wrist joint in the RSA-experiment, these differences between nonpreconditioned and preconditioned ligaments can result in considerably different force estimates for the *in vitro*, experimental situation.

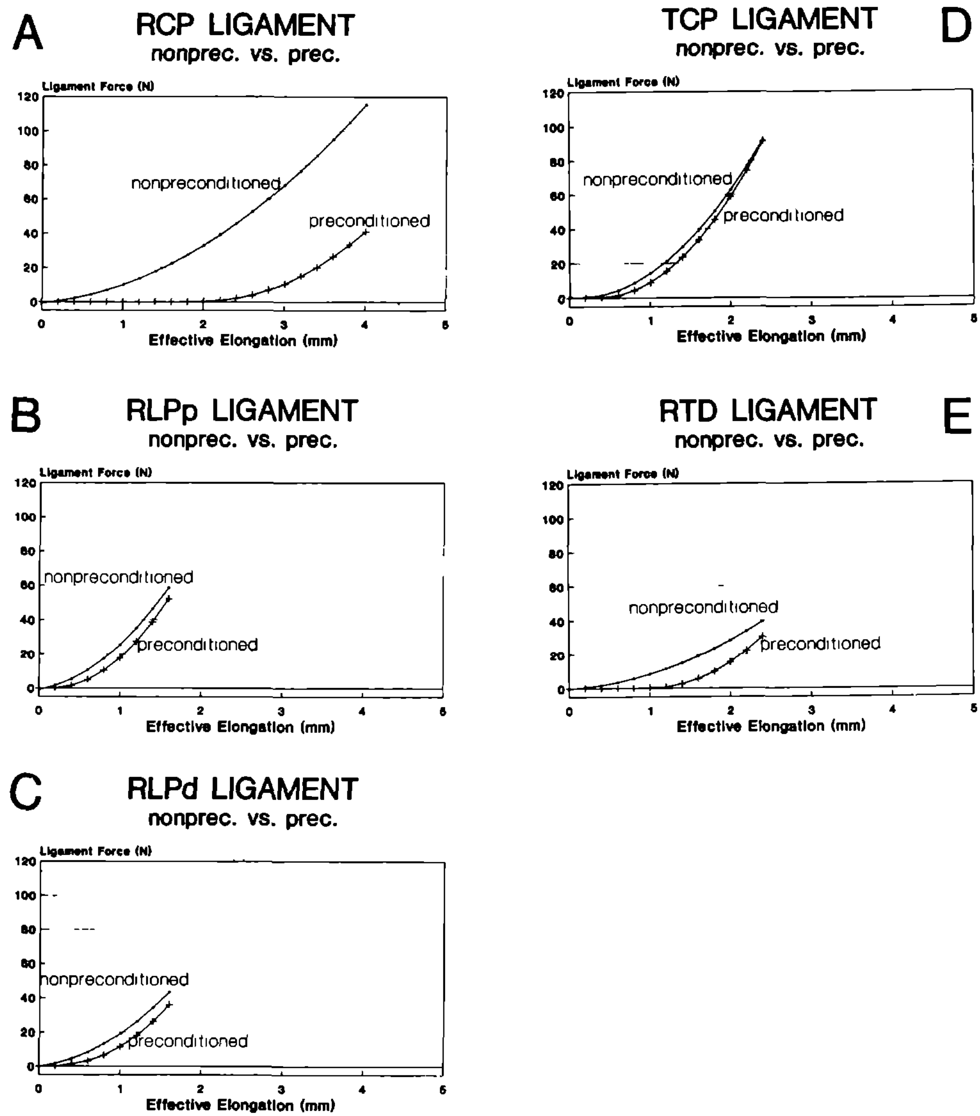


Figure 4.3 The shift to the right for the polynomial equations representing the force-elongation curves of the ligaments tested, A: RCP; B: RLPp; C: RLPd; D: TCP; E: RTD.

Forces in carpal ligaments

It is not the aim of this paper to give a complete report on carpal ligament forces. However, as a demonstration of the application for which this method is developed, effective elongation and force patterns are presented in figure 4.4, for the RTD ligament during flexion of the wrist joint.

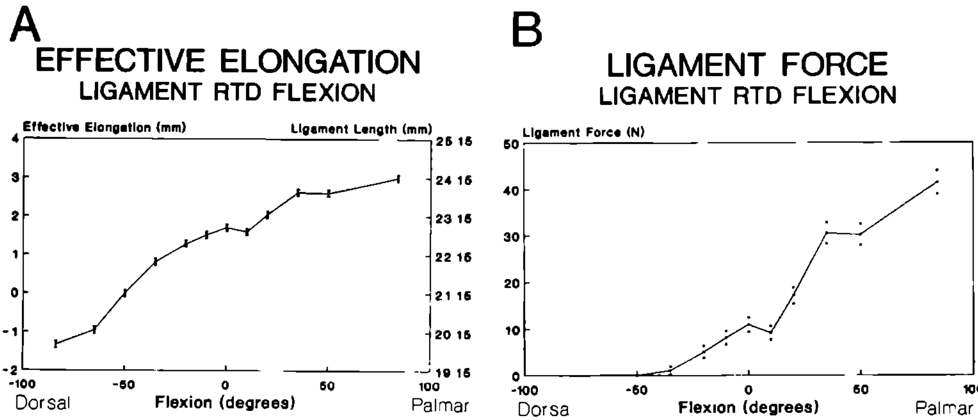


Figure 4.4 The effective elongation pattern and the ligament length (A) and the force pattern (B) for the RTD ligament during flexion of the wrist joint. In figure 4.3A the dotted lines give the standard deviations for the determination of the effective elongation, σEL; in figure 4.4B the standard deviation for the estimation of the forces, σF, are represented by dotted lines.

DISCUSSION

The results of the accuracy determination show that the present method can determine forces in ligaments rather precisely. The advantage of this method over conventional techniques like buckle-type transducers and implanted force transducers is that it does not interfere with the anatomical parts of a joint, and therefore with its moveability. The extremely small pellets glued to the ligaments in the present study cannot be assumed to have a large influence on the measurements (de Lange *et al.*, 1990c). Furthermore, the dimension of the smallest structure to be considered is only limited by the size of the pellets, which can be as small as 0.5 mm in diameter. Hence, it is possible to consider the forces in different fibres in one ligament. A disadvantage of this method is that it cannot be applied *in vivo*.

A special problem that has to be dealt with is the question whether or not the force-elongation curve should be determined from the nonpreconditioned or from the preconditioned ligament. In order to obtain reproducible and interindividually comparable force-elongation curves, it is a convention in material testing to precondition ligaments before material characteristics are determined (Fung, 1972; Viidik, 1973; Butler *et al.*, 1978; Woo *et al.*, 1983, 1986). Preconditioning is, however, not applied or mentioned in reports on direct force measurements (buckle-type transducers, implantable force transducers, etcetera) or indirect measurements (Barnes and Pinder, 1974; Huberti *et al.*, 1984; Ahmed *et al.*, 1987; Komi *et al.*, 1987; Xu *et al.*, 1990; Cummings *et al.*, 1991; Takai *et al.*, 1991). This study has shown that preconditioning affects the force estimates considerably, as a consequence of the increase of the zero-force length and probably also due to a prolonged 'toe' region in the force-elongation curve. As is suggested in the literature, the forces that are estimated in the preconditioned ligament are lower than those estimated for nonpreconditioned ligaments (Fung, 1972; Butler *et al.*, 1978; Woo *et al.*, 1983, 1986). These differences can be large enough to influence conclusions about the functional importance of the structures considered. The susceptibility to preconditioning of the force values estimated suggests that *in vivo* ligament forces may vary considerably due to the state of preconditioning of a ligament.

STRAINS AND FORCES IN SELECTED CARPAL LIGAMENTS DURING IN VITRO *FLEXION AND DEVIATION MOVEMENTS OF THE HAND* [1]

H.H.C.M. SAVELBERG, J.G.M. KOOLOOS, A. DE LANGE, R. HUISKES and J.M.G. KAUER

ABSTRACT-The forces induced in tiny wrist-joint ligaments need to be estimated in order to understand their role in the mechanism of the joint. In seven human wrist joint specimens, forces in a number of selected ligaments were estimated. A non-invasive method was applied. The method is based on the rationale that the force generated in a ligament depends on the change of length applied to the ligament. In-vitro length changes of the ligaments were determined during flexion and deviation movements of the hand, using a Röntgenstereophotogrammetric analysis (RSA) technique. Isolated bone-ligament-bone preparations were created to determine the zero-force length in a material testing machine, also using an RSA-technique, and the force-elongation relationship for the ligaments. The forces generated in the ligaments during flexion and deviation were calculated by combining results on the in-vitro ligament length changes, the zero-force length and the force-elongation relationship.

Large interspecimen variations of the force patterns were found. Due to this variability it is not possible to obtain quantitative models for the kinetic behaviour of the ligaments. However, qualitative trends could be distilled from the strain and force patterns. It is clear that for most ligaments the zero-force lengths are not equal to the lengths they possess in the neutral position of the hand. Furthermore, it could be shown during which motions of the hand a ligament is likely to be strained. It can be shown that the variations in the force patterns originate mainly from variations in the zero-force lengths and from variations in the force-strain relationships

[1] Submitted for publication.

between specimens. It is argued that it is unlikely that these variations result from real differences between individuals only. At least a part of it must be caused by artifacts in the method. Especially uncontrolled effects of frozen storage and unintentional preconditioning might influence the variation negatively. Since these artifacts are present from the first start of the experimentation, it is concluded that, at least in these specimens, the contribution of ligament forces to the kinematics of the wrist joint, which is very consistent between specimens, is of minor importance.

INTRODUCTION

Not only from a purely morphological point of view, but certainly also with respect to development and evaluation of surgical techniques, and rehabilitation procedures, it is of interest to understand the form of the carpal joint. To be able to explain the morphology of the ligaments of the carpal joint, insight in their function is required. One might say, that the general function of collagenous structures is to transduce forces. However, it is often not clear to which purposes these forces arise. To obtain insight in the precise ligament functions, the ligament forces during hand movements should be considered. In the wrist joint, forces in ligaments during hand motions have not been measured before. Nevertheless, many authors speculate about specific carpal ligament functions. It is suggested that carpal ligaments can either be considered as structures to stabilize the joint or to guide the motions of the carpal bones, they are assumed to either block or limit the movements of the carpal bones and the hand, to function as 'check-reins' or 'guy-wires', or to aid in defining the courses of motion of carpal bones (Basmajian, 1974; Mayfield *et al.*, 1976; Volz *et al.*, 1980; Bonjean *et al.*, 1981; Weber, 1984; Linscheid, 1986; Kauer and de Lange, 1987). In most cases these functions ascribed to the ligaments are based on qualitative ideas about carpal bone motions, from which ligament length changes and ligament functions are deduced. Not only the deduction of ligament function from ligament lengthening and the deduction of ligament lengthening from carpal motion is questionable, but it can also be shown that the intuitive concepts of carpal motion are not in accordance with experimentally determined carpal kinematics (Berger *et al.*, 1982; de Lange *et al.*, 1985; de Lange, 1987; Ruby *et al.*, 1988).

It is the aim of this study to determine strains and forces in a selected set of carpal ligaments during *in-vitro* flexion and deviation movements of the hand.

A method widely used to determine forces in ligaments and tendons, is the application of buckle-type transducers (Ahmed *et al.*, 1987; Barry *et al.*, 1986; Lewis *et al.*, 1982). However, this technique has the disadvantage of interfering with the course of the ligament and of possible impingement of the transducer with joint structures. Recently, other methods have been developed, omitting these disadvantages. Xu *et al.* (1990) developed a small force transducer, which can be implanted in the ligaments. The advantage of this method is that it combines direct measurements with less influence on the joint motions. However, the application to the wrist joint shows disqualifying practical implications: the ligaments in the wrist joint are very small compared to those in the knee joint, for which this implantable force transducer was developed. In addition, the high number of ligaments which have to be instrumented makes this elegant method not useful for the wrist joint. Another new method for knee joint ligaments has been presented recently by Takai *et al.* (1991). Ligament length change is calculated from experimentally determined joint kinematics. Subsequently, after dissecting soft tissue around the knee joint, load-elongation curves are recorded. *In-situ* loads are calculated by using load-elongation curves and length data together. The method we developed for carpal ligaments is similar to the one presented by Takai *et al.* (1991), albeit that the material testing in our method has to be carried out on ligaments isolated from the wrist-joint specimens. Detailed information on the method and its accuracy was reported by Savelberg *et al.* (submitted).

METHODS

Material

The wrist joints of seven freshly-frozen human cadaver specimens were considered in these experiments. Three of the seven joints were obtained from men, the other four from women. Two of the joints were from the same individual. The ages of the specimens varied between 63 and 78 years (average 68.7 ± 6.3 years). As far as the record showed, they did not suffer from diseases that influence material characteristics or mobility of the joints, abnormalities were traced by Röntgen inspection. The specimens were obtained from autopsy and stored at -20 degrees Celsius until the time of use. Although Matthews and Ellis (1968) found that the elastic modulus decreases due to frozen storage, most studies showed that this treatment does not affect the mechanical properties of ligaments (Viidik and Lewin, 1966; Noyes and Grood, 1976; Woo *et al.*, 1986). The duration of storage in frozen condition was about six months maximally. Approximately twelve hours before the start of the experiments, the frozen specimens were slowly thawed at room temperature. During the experiments the specimens remained unfrozen for four days maximally. During this time they were moistened with Ringer's solution, and when not used, stored in a refrigerator at a temperature of about 4 degrees Celsius. The experiments were carried out at room temperature, approximately 22 degrees Celsius.

In each specimen five ligaments were considered: the palmar radiocapitate ligament (RCP), the palmar radiolunate ligament (RLP), the palmar triquetrocapitate ligament (TCP), the dorsal radiotriquetrum ligament (RTD) and the dorsal triquetrotrapezium ligament (TTD). In the palmar radiolunate ligament two parts, a proximal (RLPp) and a distal half (RLPd), were examined separately. The ligaments were selected, since they are relatively easily accessible, and since other of their properties (recruitment patterns and mechanical behaviour) were already documented (Savelberg *et al.*, 1991, (accepted)).

Experimental procedure

By means of a three-step procedure, subsequent determination of (i) ligament length patterns, (ii) zero-force length, and (iii) force-elongation relationship, the forces in the selected ligament or ligament part were determined during *in-vitro* flexion and deviation movements of the hand. This method has been described in detail by Savelberg *et al.* (submitted).

Determination of the in-vitro *carpal ligament length*

The ligaments under consideration were provided with radio-opaque, tantalum pellets (ϕ: 0.5 mm). These markers were glued to the ligaments in such a way that a string of four or five pellets represented the course of a fibre along the middle of the ligament to be considered (de Lange *et al.*, 1990c; Savelberg *et al.*, 1991). Following this preparation, the specimen was positioned in a motion constraining device (de Lange *et al.*, 1985) by which flexion and deviation of the hand can be applied. For flexion the hand was moved from the so-called neutral position (that position in which radius and third metacarpal are parallel) to sites at 10, 20, 35, 50, 65 and 84 degrees palmarly, as well as dorsally. For deviation it was moved to 10, 20, 30, 40, 50, 60 and 70 degrees ulnarly and to 10, 20 and 30 degrees radially. The positions at 84 degrees palmar and dorsal flexion and 70 degrees ulnar and 30 degrees radial deviation represent the maximal excursions for the motions in the plane concerned. At each of these positions a pair of stereoradiographs was made, so that the three-dimensional location of the markers in the ligaments could be reconstructed by means of Röntgen-stereophotogrammetric analysis (RSA) (Selvik, 1974). From the 3D marker locations the ligament lengths in each position could be determined.

In three of the seven specimens, stereoradiographs were only made in the neutral position and in the four positions each corresponding to one of the maximal excursions in each direction. In these cases the ligament lengths in the intermediate positions were obtained by interpolation. From earlier results on carpal ligament recruitment (de Lange *et al.*, 1990; Savelberg *et al.*, 1991) it can be deduced that this is a valid procedure.

Determination of the zero-force lengths of ligaments

After the RSA-experiments, bone-ligament-bone (BLB) preparations containing the marked ligaments were isolated (Savelberg *et al.* (accepted)). These BLB-preparations were placed in a material testing machine in a slack position. From this situation the ligament was elongated until a load cell (MTS, Berlin, Germany), to which it was connected, registered 0.25 N force. The ligament length corresponding to this force was defined as the zero-force length of the ligament. This length was then measured by RSA, using a pair of stereoradiographs of the ligament in the material testing machine, which still contained the tantalum markers (Figure 5.1).

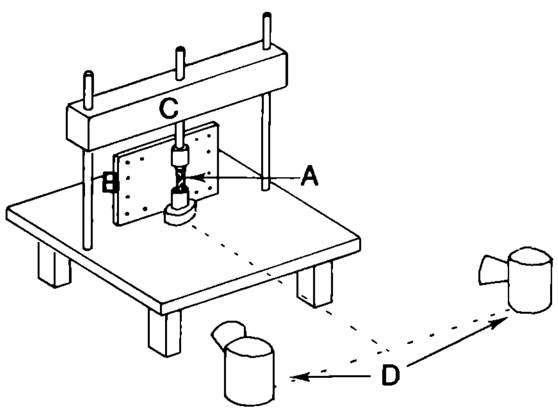


Figure 5.1 The experimental set-up for the determination of the zero-force length: A: the bone-ligament-bone specimen provided with tantalum pellets; B: Röntgen filmholder; C: material testing machine; D: two Röntgen tubes.

Determination of the force-elongation relationship

The final step in the experimental procedure is the determination of the force-elongation relationship. The ligament was strained 15% at a rate of 66 %/sec of its initial length. Simultaneously, the force developed in the ligament was sampled at 200 Hz. This part of the experiment immediately followed the zero-force length determination; in between the ligament was not removed from the material testing machine. The ligaments were not preconditioned. The consequences of this are discussed later.

The initial length was determined by a pair of vernier callipers before the ligament is positioned in the material testing machine. It is just measured to estimate the maximal strain and the strain rate to be applied to the ligament.

Data processing

For each position of the joint in the RSA-experiment the amount of strain in a ligament is calculated according to:

$$\varepsilon(p) = \frac{L(p) - L_{ZF}}{L_{ZF}}, \qquad (5.1)$$

where ε(p) is the amount of strain with the hand in position p, L(p) is the ligament length (mm) with the hand in position p, as determined in the RSA-experiment, L_{ZF} is the zero-force length (mm) of the ligament. Plotting these strains against the motion of the hand results in strain patterns.

From the force samples and the elongation applied to the ligament the force-elongation relationship is assessed by fitting a second degree polynomial equation to these data, according to:

$$F = aL^2 + bL + c, \qquad (5.2)$$

where F is the ligament force (N), a,b and c are constants determining the force-elongation relationship, L is the elongation (mm) applied to the ligament.

From the actual ligament length L(p) in a given position of the hand, the effective elongation, that is the amount of lengthening that contributes to force development in the ligament, can be calculated by subtraction of the zero-force length:

$$EL(p) = L(p) - L_{ZF}, \qquad (5.3)$$

where EL(p) is the effective elongation of a ligament with the hand in position p.

The force developed in a ligament in a certain position of the hand, F(p) is given by substituting the variable L in equation (2) by the amount of effective elongation in that position of the hand. Plotting these forces against the position of the hand results in the ligament force patterns.

Accuracy

In an earlier study we showed that the method described for the determination of forces in carpal ligaments is accurate (Savelberg *et al.* (submitted)). The measurement error was shown to depend on the effective elongation and the current stiffness of a ligament, which, in the non-linear part of the force-elongation curve, also depends on the effective elongation. For ligament strains of approximately 15% of the zero-force length it appeared that the standard error of the force-determination is about 5% of the force estimated.

A total of nine ligament strings were not evaluated. This concerned three RLPp ligaments, three RLPd ligaments, two TCP strings, and one TTD ligaments. The reasons to discard these data were twofold. First of all, in some cases the reconstructions of the ligament strings in the RSA-evaluations could not be performed because of obvious errors in the pellet identification. Secondly, some pellets were lost in the BLB-preparations.

RESULTS

In most of the ligaments tested the strain patterns display similar tendencies over the specimens. However, a large variation between actual strain values of corresponding ligaments over the specimens is found. This variation can rise to 15% of the zero-force length between the most strained and the least strained ligament at a particular flexion or deviation angle of the wrist joint. Compared to the variation in the recruitment patterns (Figure 5.2A), the variation in the strain patterns is considerably higher (Figures 5.2B). The variations of the recruitment patterns resemble those reported by de Lange *et al.* (1990c) and Savelberg *et al.* (1991). The differences between the most recruited and the least recruited ligaments are maximally 5% of the length in the neutral position of the hand.

The variations in the force patterns are even higher than those in the strain patterns (Figure 5.2D). The difference between the highest and the lowest force in ligaments can amount up to 70 N, in the same hand position. Partly this difference results form different strain patterns, but also the variability of the force-strain relationships contributes to is (Figure 5.2C).

Deviation

In deviation the **RCP** ligament lengthens when the hand is moved ulnarly. The position in which the zero-force length is reached in different specimens ranges from about 20 to 70 degrees ulnar deviation (Figure 5.3A). In maximal ulnar deviation the strain varies between 0 an 10%. The variation in the force patterns amounts to 60 N maximally in extreme ulnar deviation

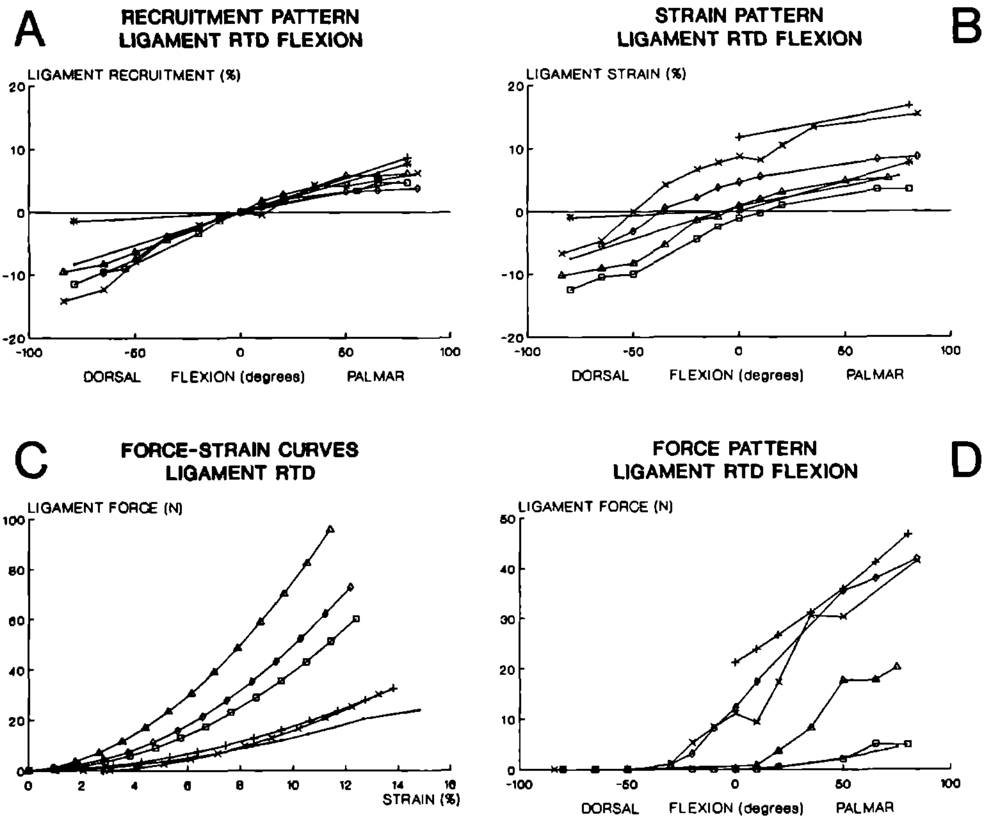


Figure 5.2 *The increasing variability of the patterns from different specimens, when subsequently recruitment patterns (A), strain patterns (B) and force patterns (D) are determined. The variability of the force-strain relationship over the RTD ligaments tested (C).*

of the hand (Figure 5.3B). Of the seven specimens tested, the RCP ligaments are loaded in only three.

Contrarily to the general trend, the strain patterns of the **RLPp** ligaments during deviation of the hand are very consistent (Figure 5.4A). During deviation movements of the hand the strains in the RLPp ligament hardly changes. For the ligaments tested, the strain varied only between 5 and 10%, the length of each ligament is always larger than the zero-force length. The force patterns show more variations (Figure 5.4B). At maximal radial deviation they range between 5 and 35 N. The data of three of the seven RLPp ligaments were not taken into consideration, because of artifacts in the ligament length or zero-force length measurements.

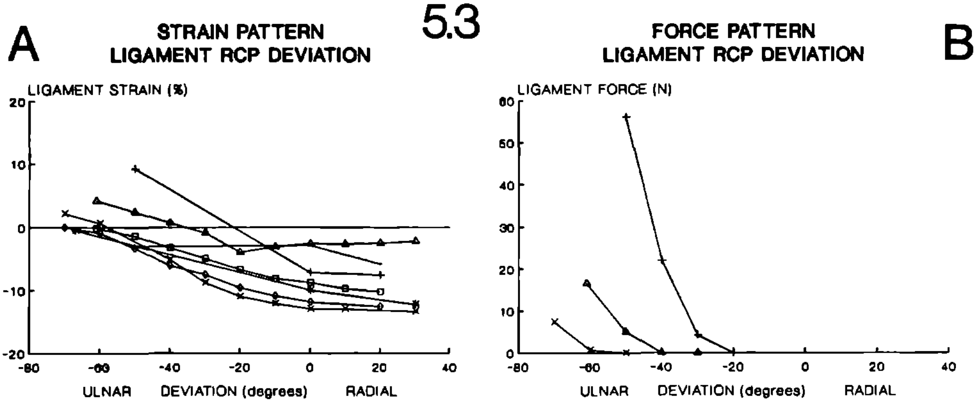
Due to artifacts, the **RLPd** strain and force patterns of only four specimens could be included. The ligament was hardly strained in most of the wrist joints. In two of the four remaining ligaments some forces were developed. However, their patterns were quite inconsistent.

During deviation, the **TCP** ligaments were hardly strained. Consequently, also the forces generated in the ligaments were very small or zero. All TCP ligaments tested displayed a tendency to lengthen when the hand was moved from maximal ulnar deviation to the neutral position of the hand. During neutral to radial deviation the length changes levelled off. The dispersion between the strain patterns was over 10% of the zero-force length, between the most and least strained ligaments.

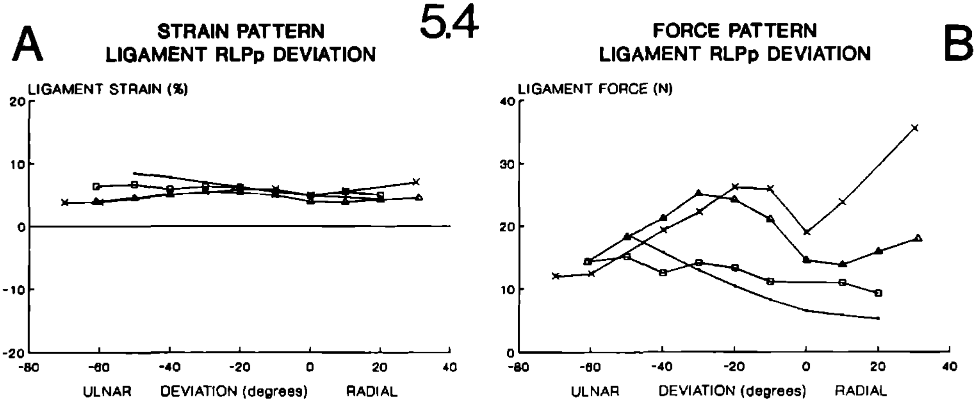
The **RTD** ligaments all elongated when the hand was moved from an ulnarly deviated position radially. Between 20 degrees ulnar deviation and maximal radial deviation the ligament length hardly changes. The hand position in which the zero-force length was reached varied between 40 and 0 degrees ulnar deviation (Figure 5.5A). In one of the specimens tested the zero-force length was not reached at all. Another was constantly strained by about 10%. The force patterns were rather consistent in six of the seven specimens tested. They showed maximal values of approximately 5 to 7 N between 20 degrees ulnar deviation and the neutral position of the hand (Figure 5.5B).

The length changes in the **TTD** ligaments were small in deviation of the hand, approximately 2% of the zero-force length. The ligaments become longer when the hand is ulnarly deviated. The ligaments were almost constantly strained. The variation over the specimens amounted to about 10% between the most and the least strained specimens. This variation in the strain patterns notwithstanding, the force patterns were very similar. The force values were very small, 2 N maximally in ulnar deviation.

5.3


A
STRAIN PATTERN
LIGAMENT RCP DEVIATION
LIGAMENT STRAIN (%)
20
10
0
-10
-20
-80
-60
-40
-20
0
20
40
ULNAR DEVIATION (degrees) RADIAL
B
FORCE PATTERN
LIGAMENT RCP DEVIATION
LIGAMENT FORCE (N)
60
50
40
30
20
10
0
-80
-60
-40
-20
0
20
40
ULNAR DEVIATION (degrees) RADIAL

5.4


A
STRAIN PATTERN
LIGAMENT RLPp DEVIATION
LIGAMENT STRAIN (%)
20
10
0
-10
-20
-80
-60
-40
-20
0
20
40
ULNAR DEVIATION (degrees) RADIAL
B
FORCE PATTERN
LIGAMENT RLPp DEVIATION
LIGAMENT FORCE (N)
40
30
20
10
0
-80
-60
-40
-20
0
20
40
ULNAR DEVIATION (degrees) RADIAL

5.5

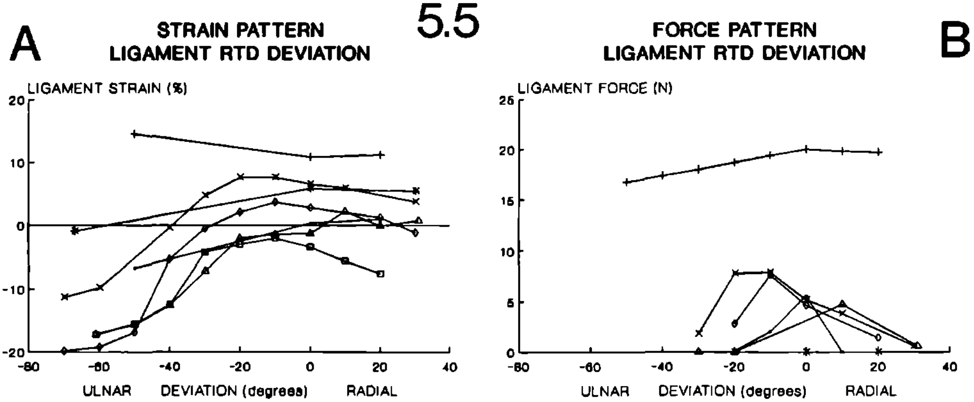

A
STRAIN PATTERN
LIGAMENT RTD DEVIATION
LIGAMENT STRAIN (%)
20
10
0
-10
-20
-80
-60
-40
-20
0
20
40
ULNAR DEVIATION (degrees) RADIAL
B
FORCE PATTERN
LIGAMENT RTD DEVIATION
LIGAMENT FORCE (N)
25
20
15
10
5
0
-80
-60
-40
-20
0
20
40
ULNAR DEVIATION (degrees) RADIAL

Figure 5.3, 5.4 and 5.5 The strain (A) and force patterns (B) for the RCP (figure 5.3), RLPp (figure 5.4) and RTD ligaments (figure 5.5) in the seven specimens tested during deviation of the hand.

Flexion

During flexion the **RCP** ligaments were elongated when the hand was moved dorsally. The elongation can amount up to 20% of the zero-force length over the whole flexion movement, that is from maximal palmar to maximal dorsal flexion. For the specimens tested the positions of the hand where the zero-force lengths were reached, were between 15 and 80 degrees dorsal flexion (Figure 5.6A). The maximal strains varied from 0 to 18%. In the force patterns similar large differences were found. In maximal dorsal flexion the force values ranged between 0 and 60 N (Figure 5.6B). The force patterns were very similar, however.

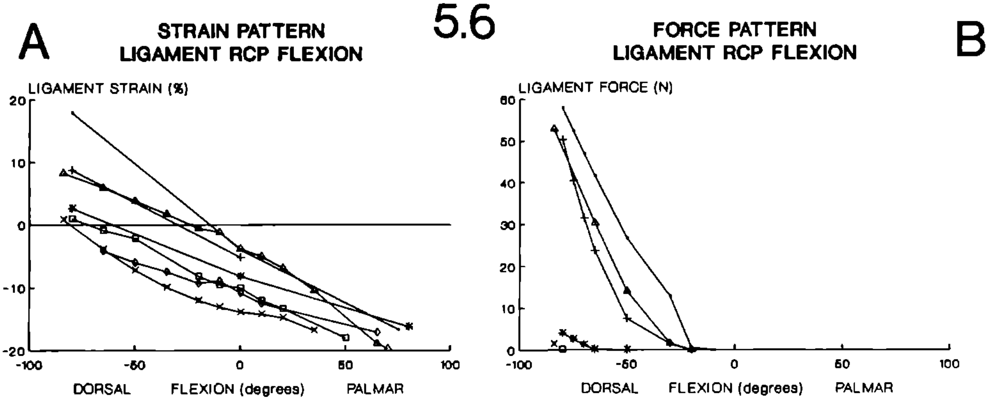
The variation in the strain patterns of the **RLPp** ligament during flexion of the hand was about 10% of the zero-force length. The flexion angle of the hand at which the zero-force length was reached varied between 15 degrees dorsal flexion and 70 degrees palmar flexion. The force patterns show that the ligaments were loaded during a large part of the movement range in some of the specimens, while in other specimens, the ligament was hardly strained or loaded.

The strain and force patterns of three of the four **RLPd** ligaments tested were very similar. They reached their zero-force length close to the neutral position of the hand. The fourth ligament specimen is strained throughout the whole motion. All four specimens were lengthened when the hand was moved dorsally from any position (Figure 5.7A). The force patterns of those three specimens with similar strain patterns resemble each other very well. During the greater part of the motion, none or only small forces were generated, however, when the hand was moved close to its maximal dorsal position the ligament forces start to rise (up to 10-15 N). The one ligament which had a deviating strain pattern, also displayed a different force pattern (Figure 5.7B).

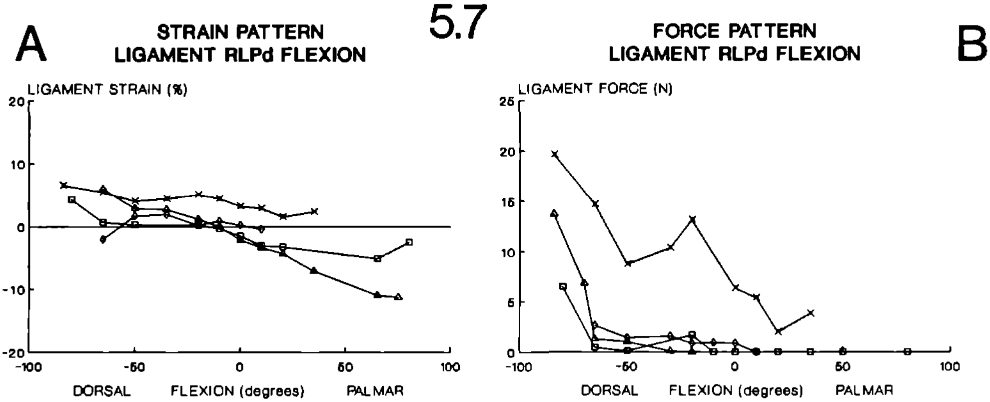
The **TCP** ligaments hardly elongated during flexion of the hand. The variation in the strain patterns was some 10%. Some of the ligaments were a few percents strained constantly, while others remained unstrained throughout the whole flexion movement. The forces developed were small, less than 5 N.

The **RTD** ligaments became elongated when the hand was moved palmarly. The length changes amounted to up to 20% of the zero-force length. Over the specimens tested the zero-force lengths were reached when

5.6


A
STRAIN PATTERN
LIGAMENT RCP FLEXION
LIGAMENT STRAIN (%)
20
10
0
-10
-20
-100
-50
0
50
100
DORSAL
FLEXION (degrees)
PALMAR
B
FORCE PATTERN
LIGAMENT RCP FLEXION
LIGAMENT FORCE (N)
60
50
40
30
20
10
0
-100
-50
0
50
100
DORSAL
FLEXION (degrees)
PALMAR

5.7


A
STRAIN PATTERN
LIGAMENT RLPd FLEXION
LIGAMENT STRAIN (%)
20
10
0
-10
-20
-100
-50
0
50
100
DORSAL
FLEXION (degrees)
PALMAR
B
FORCE PATTERN
LIGAMENT RLPd FLEXION
LIGAMENT FORCE (N)
25
20
15
10
5
0
-100
-50
0
50
100
DORSAL
FLEXION (degrees)
PALMAR

5.8

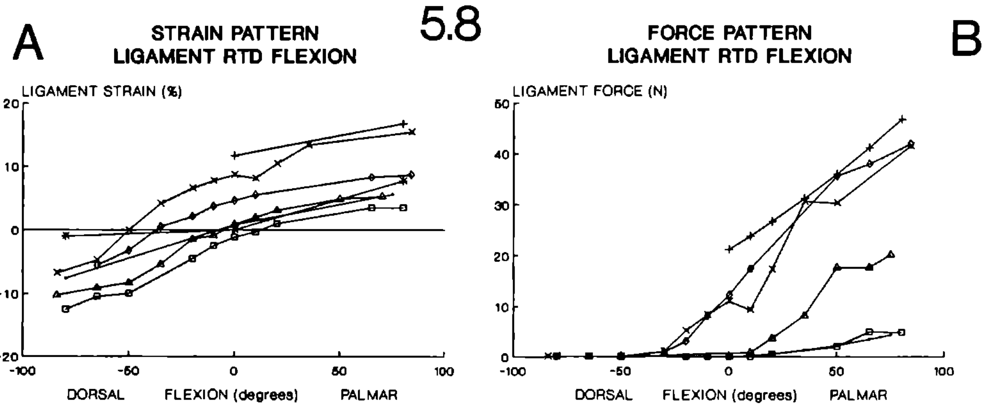

A
STRAIN PATTERN
LIGAMENT RTD FLEXION
LIGAMENT STRAIN (%)
20
10
0
-10
-20
-100
-50
0
50
100
DORSAL
FLEXION (degrees)
PALMAR
B
FORCE PATTERN
LIGAMENT RTD FLEXION
LIGAMENT FORCE (N)
50
40
30
20
10
0
-100
-50
0
50
100
DORSAL
FLEXION (degrees)
PALMAR

Figure 5.6, 5.7 and 5.8 The strain (A) and force patterns (B) for the RCP (figure 5.6), RLPd (figure 5.7) and RTD ligaments (figure 5.8) in the seven specimens tested during flexion of the hand.

the flexion angle was between 50 degrees dorsal flexion and 5 degrees palmar flexion. The variation in the strain at a particular flexion angle was between 5 and 10% of the zero-force length (Figure 5.8A). The variations of the force patterns ranged up to 40 N in maximal palmar flexion. The trends in the force patterns were consistent (Figure 5.8B).

The strain and force patterns for the TTD ligament during flexion were similar to those in deviation. Only small forces were generated. The strains were more or less constant per ligament, but displayed a variation of 5 to 10% of the zero-force length over the specimens.

DISCUSSION

In spite of the high variability in the ligament forces determined, some interesting features concerning the ligament behaviour can be shown from the present results, based on trends in the patterns. For most ligaments, the RCP, the RLPp, the RLPd and the TTD ligament during deviation, and the RCP, the RLPp, the TCP, the RTD and the TTD ligament during flexion of the hand, it can be concluded that their lengths in the neutral position of the hand do not equal the zero-force lengths. The RCP ligament seems to be unloaded in the neutral position of the hand. When the hand is moved ulnarly or dorsally this ligament is strained. The ulnar deviation or dorsal flexion angle at which this occurs is variable. The RLPp ligament seems to be loaded when the hand is in the neutral position. The effect of ulnar or radial deviation on the amount of loading is small, at least for the excursions studied here. Dorsal flexion seems to result in higher loads, while palmar flexion unloads this ligament. The behaviour of the RLPd ligament during deviation of the hand is unclear. In flexion it is likely that this ligament becomesloaded, when the hand is moved dorsally from the neutral position. For the RLPd ligament the length in the neutral position of the hand seems to correspond to the zero-force length. The strain and force patterns of the TCP ligament, both for flexion and deviation of the hand, cannot be interpreted unequivocally. The RTD ligament can be considered to become loaded during deviation of the hand, when the hand is close to the neutral position. Ulnar deviation unloads this ligament, while radial deviation will not affect the load. During flexion of the hand the RTD ligament becomes loaded when the hand is moved palmarly. The dorsal flexion angle at which this occurs is variable, and not too great. In the neutral position the ligament is loaded. The strain and force patterns for the TTD ligament suggest that this ligament becomes loaded only when extreme dorsal flexion or ulnar deviation positions are reached, however, the forces generated are small.

A major point of interest is the high interspecimen variability in the force patterns, which are found in these experiments. In fact three levels can be indicated where these variations can emerge: (i) variability in carpal kinematics, reflected in ligament length patterns during motions, (ii) variability in the zero-force length, and (iii) variability in the force-elongation relationships. When the recruitment patterns, strain patterns and force patterns are considered, it appears that a major increase of variation occurs between recruitment and strain patterns (Figures 5.2A and B). The variation in the force patterns (Figure 5.2D) is partly the reflection of these variable strain patterns. Another part of the variation in the force patterns appears to have its origin in the variability of the force-strain relationships (Figure 5.2C). Hence, from these experiments the suggestion rises that a larger part of the interspecimen variation in the force patterns can be attributed to variations in the material characteristics between specimens: the zero-force lengths and the force-strain relationships.

These variations may reflect either real interindividual differences, artifacts introduced by the measurement procedure or measurement errors.

The contribution of measurement errors has been discussed by Savelberg *et al.* (submitted). These errors, due to inaccuracies in the 3D marker reconstruction and polynomial fitting of the force-elongation samples, were small compared to the variation between the specimens found in the present study. They amounted maximally to about 5% of the forces estimated.

One causative factor of artifacts could be the method of storing. There is consensus in the literature that frozen storage does not significantly affect the biomechanical properties of connective tissue (Viidik and Lewin, 1966; Matthews and Ellis, 1968; Noyes and Grood, 1976; Woo *et al.*, 1986). Certainly the collagenous fibres keep their properties, which is reflected in the unchanged elastic components of the tissue behaviour, reported in most of these studies. Woo *et al.* (1986), however, suggested that the cells and the ground substances might be affected. This could change the fluid movements (Stouffer and Butler, 1984) and influence the non-linear, viscoelastic behaviour of the ligaments. Hence, primarily the toe-regions of the force-elongation curves could be affected. It is not unlikely, therefore, that variability in the zero-force length determination, is caused by storing effects, since it is based on an extremely small force threshold of 0.25 N.

The susceptibility of the force-elongation curves and the zero-force lengths to preconditioning can be another source of artifacts. It is not unthinkable that some of the isolated ligaments, although treated with care, were accidentally strained a little while mounting them to the tensile testing machine. This may have affected the zero-force lengths in particular (Savelberg *et al.* (submitted)), but probably only to a lesser extent.

The alignment of the wrist-joint specimens to the RSA set-up and that of the isolated BLB-preparation to the tensile testing machine are a third and fourth potential artifacts to be considered. Slight rotations of the joint specimens around their longitudinal axes would result in slightly different recruitment patterns. However the recruitment patterns for different specimens are very similar (Figure 5.2A). Therefore, it can be concluded that the influence of such an artifact will be small. The same holds for the alignment of the BLB-preparations. Proper alignment is taken care of by selecting the best of three independent trials. Furthermore, in a previous study the tangent moduli of the wrist-joint ligaments were determined in a similar way (Savelberg *et al.* (accepted)), in that study no extraordinarily large variations over the specimens were found. It was concluded that the method was accurate.

This leads to the conclusion that the variability may well be explained by artifacts affecting the zero-force lengths of the ligaments, with freezing and unintentional, slight preconditioning as the main causative factors. Other potential artifacts, however, are not likely to have major effects. On the one hand, the results of the length patterns are very consistent, also with previous studies (de Lange, 1987; de Lange *et al.*, 1990c; Savelberg *et al.*, 1991). On the other hand, the force patterns are highly variable. Since the main artifacts, effects of freezing and unintentional, slight preconditioning, are already present from the first moment of experimentation, this simply leads to the conclusion that, at least in the specimens studied, the wrist behaves kinematically consistent, but kinetically variable. This would imply, that mechanical behaviour of the wrist is predominantly determined by articular geometry, and not by ligament constraints.

CARPAL BONE KINEMATICS AND LIGAMENT LENGTHENING STUDIED FOR THE FULL RANGE OF JOINT MOVEMENT [1]

H.H.C.M. SAVELBERG, J.D.M. OTTEN, J.G.M. KOOLOOS, R. HUISKES and J.M.G. KAUER

ABSTRACT*-Present data on carpal kinematics and carpal ligament behaviour are limited to flexion and deviation movements of the hand. These motions do not represent all the wrist-joint motions which are important for the activities of daily living. The goal of this project was to obtain insight in carpal kinematics and carpal ligament behaviour during motions of the hand covering the full range of motion of the wrist joint.*

The carpals and the ligaments of four wrist-joint specimens were provided with radio-opaque markers. These joints were subjected to Röntgenstereophotogrammetric experimentation in a large number of hand positions to determine carpal positions and ligament lengths. The movements of the carpal bones were described by means of finite helical axes (FHA).

It was found that the movements of the carpals in the distal row closely resemble those of the hand. Conversely, the motions of the carpals of the proximal row appeared to be not directly proportional to the hand motions and exhibited clear out-of-plane movements. It could furthermore be shown that movements of the hand into the ulnodorsal quadrant of the full range of hand motion corresponds to larger helical rotations and translations for most of the carpals than when the hand was moved into another quadrant. The maximal ligament length changes determined did not exceed the length changes reported for pure flexion and pure deviation movements of the hand.

[1] Submitted for publication.

INTRODUCTION

Many studies of the wrist-joint have been conducted to investigate its behaviour as a mechanism and to study relationships between form and function. For instance, the kinematic behaviour of the carpal bones were measured under prescribed hand displacements (Kauer, 1974; Youm and Flatt, 1980; Berger *et al.*, 1982; de Lange *et al.*, 1985; de Lange, 1987; Ruby *et al.*, 1988), the length changes or strains in ligaments were measured (Bonjean *et al.*, 1981; Mayfield *et al.*, 1976; Taleisnik, 1976; de Lange *et al.*, 1990c; Savelberg *et al.*, 1991) or the forces in ligaments were estimated (Savelberg *et al.*, submitted). These experiments were usually conducted during flexion and deviation movements of the hand relative to the forearm. However, these selected movements do not cover the complete range of bone positions during daily activities (Palmer *et al.*, 1985). Hence, it is uncertain whether information thus obtained provides complete understanding of the wrist-joint behaviour and function.

In this study, we expanded the wrist-joint movements studied to combined flexion and deviation movements, covering the full range of motion. The three dimensional carpal movements during pure flexion or pure deviation of the hand have been established (Berger *et al.*, 1982; de Lange *et al.*, 1985; Ruby *et al.*, 1988). It is questionable, whether carpal movements during other movements of the hand can be derived from the known carpal displacements during pure flexion and pure deviation. Insight in carpal kinematics as a function of hand motions covering the full range of movements of the wrist joint will contribute to better understanding of the wrist-joint mechanism. It was shown that in maximal flexion and maximal deviation of the hand the carpal ligaments become only slightly strained (Savelberg *et al.*, submitted). From the same experiments it appeared that distinctly higher loads can be applied to wrist-joint ligaments without inducing irrecoverable damages. Hence, it seems that during pure flexion or deviation of the hand the loadability of the carpal ligaments is not fully used. It might be that during other hand motions the ligament strains are higher.

In this study the kinematics of selected carpal bones and the length changes of carpal ligaments were determined, during motions of the hand relative to the forearm, covering its full range of motion.

METHODS

Material

Four human cadaver wrist joints were obtained from autopsy. All four joint specimens were from male donors, two of the specimens originated from one individual, the other two were left-handed. The ages of the donors ranged between 61 and 77 years (mean: 68 years) (Table 6.1). For as far as the record showed, the donors did not suffer from diseases which could affect the kinematic behaviour of the joint. The specimens were stored frozen until time of use. For two of the four specimens the storage time amounted to six months, the two other specimens had been used in earlier experiments and had been stored frozen twice; for about six months before the earlier experiments and about one and a half year between these earlier experiments and the current investigations. Several studies showed that freezing does not significantly affect the mechanical properties of connective tissue (Viidik and Lewin, 1966; Matthews and Ellis, 1968; Noyes and Grood, 1976; Woo *et al.*, 1986).

Experimental procedure

To impose displacements of the hand relative to the forearm, the specimens were positioned in a motion constraining device (de Lange *et al.*, 1985). This fixture, to which the radius was secured, includes a number of constant-force springs to which the tendons of the muscles crossing the wrist joint were connected, and a graduated arc, by which the motion range of the joint can be determined (Figure 6.1). Originally, this apparatus had been designed for planar motions, pure flexion or pure deviation of wrist-joint specimens, resulting in a semicircular sample of data (Figure 6.2A). This study required the application of spatial movements of the hand, so that a semisphere of hand positions could be sampled (Figure 6.2B). To meet this demand in the motion constraining device, the specimens were subsequently rotated about a longitudinal axes in the radius, and in each of those rotated positions a semicircular set of samples belonging to one planar motion pathway was obtained. A number of rotated semicircular sets of samples generate a reasonable representation of the required semisphere of hand positions.

To determine the movements of the carpal bones and the length changes of the carpal ligaments during the imposed movements of the hand, the technique of Röntgenstereophotogrammetric analysis (RSA), developed by Selvik (1974, 1989) was used. The carpal bones and ligaments of the

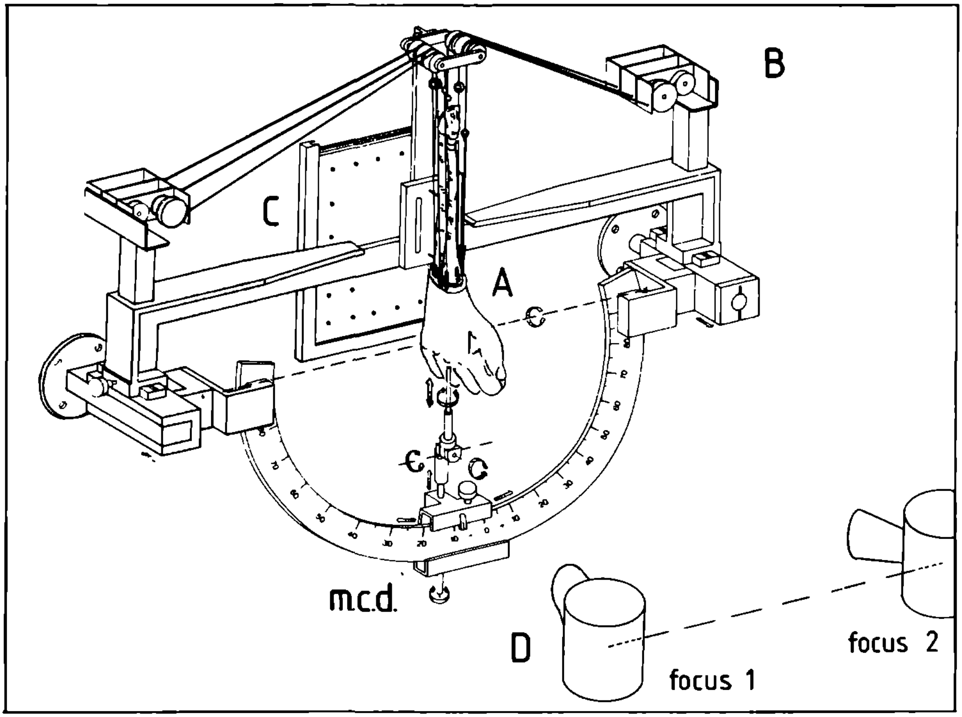


Figure 6.1 *The motion constraining device to which the specimens (A) were fixed during the RSA-experiment. (Reprinted with permission from Raven Press, Ltd./New York from* Journal of Orthopaedic Research, *Wrist-joint ligament length changes in flexion and deviation of the hand: an experimental study, vol.8, 722-730).*

specimens were provided with Röntgen-opaque markers (tantalum pellets), whose 3D positions could be reconstructed based on a pair of stereo radiographs. The ligaments were provided with four or five tantalum pellets along a fibre in the middle of the superficial layer of the ligament, with one of the markers on the origin, one on the insertion site and the remaining two or three in-between. It is assumed that the length of the ligament was properly represented by the summation of the intervals between adjacent markers (de Lange *et al.*, 1990c). The carpals were provided with at least three markers, but usually four or five. Three noncollinear markers is the minimal amount required to model a bone as a rigid body. It was chosen not to mark all carpal bones and ligaments. Table 6.1 gives an overview of which carpal bones were considered in each specimen. The results of de

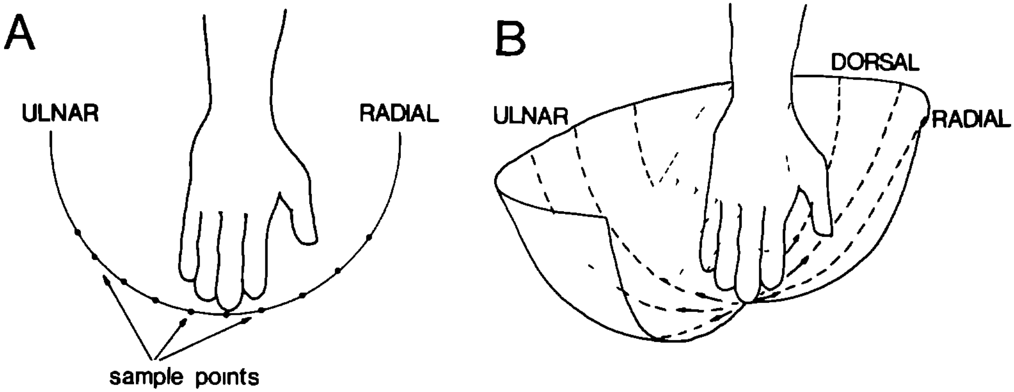


Figure 6.2 *A: A semicircular set of sample points, which can be acquired during standard planar hand displacement in the motion constraining device (Figure 6.1).*
B: The semispherical movement space of the hand, which can be sampled by a number of longitudinally rotated planar semicircular displacements.

Lange *et al.* (1985), de Lange (1987), Berger *et al.* (1982) and Ruby *et al.* (1988) have shown that the carpal bones of the distal row (trapezium, trapezoid, capitate and hamate) have similar movement patterns, whereas those of the proximal carpal row (scaphoid, lunate and triquetrum) tend to move differently. The fibres of the palmar ligamentous complex between radius and capitate (RCP), and between radius and lunate (RLP) were considered. In the wide RLP ligament, not just one but two fibres, a proximal (RLPp) and a distal one (RLPd), were marked. On the dorsal side of the joints, ligamentous structures between radius and triquetrum (RTD) and triquetrum and trapezium (TTD) were represented by a string of radio-opaque pellets. For a more detailed description of these ligaments see de Lange *et al.* (1990c) and Savelberg *et al.* (1991).

After the specimens were prepared in this way, they were positioned in the motion constraining device (Figure 6.1). By a Steinmann pin in the third metacarpal bone they were connected to a carri age which could be moved along the graduated arc, and by which the displacement of the hand was applied. The motion constraining device was placed in a set-up with two Röntgen tubes

Table 6.1 *An overview of the carpal bones considered in each of the specimens, and the ages of the four specimens.*

SPECIMEN	1	2	3	4
AGE	61	61	72	77
LUNATE	X	X	X	X
CAPITATE	X	X	X	X
SCAPHOID	X	X	X	X
TRAPEZIUM	X	X	-	-
TRIQUETRUM	-	-	-	X

and an X-ray film cassette holder (Figure 6.1). At the beginning of the experiment the specimen was positioned with the hand in the so-called neutral position relative to the forearm, that is the position in which the third metacarpal bone and the radius are parallel. The radial side of the hand faced the X-ray film cassette holder and the ulnar side faced the Röntgen tubes. The motion which could be applied to the hand in this case, was a pure flexion movement. In this position a pair of stereo radiographs was made. The maximal excursion was determined subjectively. When the force resisting further hand displacement was judged as being so high that further motion could damage the joint, the end position was considered to be reached. Subsequently the hand was moved along the graduated arc to several palmar and dorsal flexion position. In each position a pair of stereo radiographs was made. After the movement possibilities in this plane, *viz.* along this motion pathway, were satisfactorily sampled, the specimen was rotated approximately 30 degrees about the longitudinal axis of the radius. Now the plane of the movement direction of the hand in the motion constraining device became somewhat ulnodorsal and radiopalmar or, when the radius was rotated the other way around, ulnopalmar and radiodorsal. Along this motion pathway stereo radiographs were also made after several motion steps. By continuing the rotation about the radius the whole semisphere of potential hand positions could be sampled.

As this method, and especially the subsequent data processing, are very time-consuming and tedious, it was chosen not to carry out the same ranges of hand motions for each of the four specimens, but to cover the motion range in each of the specimens only partly. The distribution of the applied hand motions over the specimens gave a complete image of the carpal kinematics and ligament length changes and allowed the generalization of these data.

Dataprocessing

When the images of the markers on the stereo radiographs were digitized, the 3D coordinates of the markers were reconstructed using stereophotogrammetric principles (Selvik, 1974, 1989). From these 3D marker positions, the 3D motions of all carpal bones relative to the radius, the rotations applied to the radius relative to its neutral position and the length changes of the ligaments were calculated.

Carpal motion

The 3-D carpal displacements were described as rigid-body motions by three, mutually perpendicular Eulerian rotation angles and three translation vectors. To determine the Eulerian angles, body-fixed coordinate systems were introduced in all carpal bones concerned. The orientations of these body-fixed coordinate systems were such that they coincided with the orientation of the coordinate system in the radius in the neutral position of the hand (de Lange *et al.*, 1985). The rotations were determined in the sequence: flexion motions about the x-axis, deviations motions about the y-axis and finally pro/supination motions about the z-axis. This coordinate system was defined so as to be anatomically relevant: a positive, right-hand rule rotation about the x-axis signified palmar flexion; a similar rotation about the y-axis signified radial deviation; and the positive, right-hand rule rotation about the z-axis signified supination. The data from the right-hand specimens were transformed to a left-hand one to enable easy comparison.

The rigid body motions of the carpals were also represented by finite helical axes (FHA; de Lange *et al.*, 1990b), calculated according to Rodrigues' formula (Selvik, 1974, 1989). The FHA's can be determined for each carpal bone relative to every other carpal bone or relative to the fixed radius. In this study the FHA's for the motions of the carpal bones relative to the fixed radius and relative to the neighbouring carpals as functions of the applied hand displacements were determined. FHA's are defined by their positions in space and their directions. The magnitude of the displacements are described by the rotation about the axis and the translation along the axis. The positions and directions of the helical axes in this study were defined relative to a right-hand rule laboratory coordinate system to which the radius was fixed. The x-axis was ulnarly directed, the y-axis palmarly and the z-axis proximally.

The position of the pivot point (de Lange, 1987), where the axes for the motions of a particular carpal bone relatively to the radius cross each other, was calculated. It was defined as the point with the smallest root mean square (r.m.s.) distance (D) to the FHA's involved (Woltring, 1990). The magnitude of the r.m.s. distance (D) determines the closeness of the FHA's to the pivot point. When the r.m.s. distance (D) would be equal to zero, all FHA's would have the same position vector. If D is relatively small, the position vectors are approximately equal. Furthermore, the angular dispersion between the FHA's, describing the resemblances between the directions of the axes, was calculated. For this purpose a mean helical axis (MHA) was calculated by minimizing the r.m.s. values of the sinuses of the angles between the MHA and the FHA's. The angular dispersion (χ (chi)) was defined as the arcsine of these r.m.s. values (Woltring, 1990).

Ligament length change

The ligament length was defined as the summation of the distances between adjacent markers in a ligament (de Lange *et al.*, 1990c). The length changes were expressed as percentages of the length of the ligaments with the hand in the neutral position. As the length in the neutral position did not necessarily equal the zero-force length of the ligament (Savelberg *et al.*, submitted), the relative length does not equal the strain in a ligament.

The recognition of the ligament markers on the stereo radiographs was not reliable in a number of cases. Only the data which could be determined reliably were considered in this paper.

RESULTS

Mobility of the hand

The motion protocols which were applied to the four specimens are presented in figure 6.3. In specimen one an almost complete sampling collection of the movement range of the wrist joint was obtained. In the other three specimens this range was only partly covered: the extreme excursions along several motion pathways, resulting in figure 6.3 in the envelope of movement (specimen two); two quarters of this envelope (radiopalmar and ulnodorsal) (specimen three); and in the fourth specimen a single quadrant (ulnodorsal) of the motion range. When the hand is moved radially the range of displacement of the hand relative to the forearm is smallest, approximately 30 degrees. In ulnar deviation the maximal reach is about 70 degrees, while in maximal dorsal and palmar flexion the mobility amounts about 85 degrees. When the maximal excursion of the hand for the different movement directions are plotted in a 2D picture, a kidney-shape range of wrist joint movement with a concavity on the radial side results, as is shown in figure 6.3.

Presentation of kinematic data

To present the Euler rotation angles, third or fourth order polynomials as functions of the 2D (combined deviation and flexion) movement of the hand were fitted to each of the rotation angles (flexion, deviation and

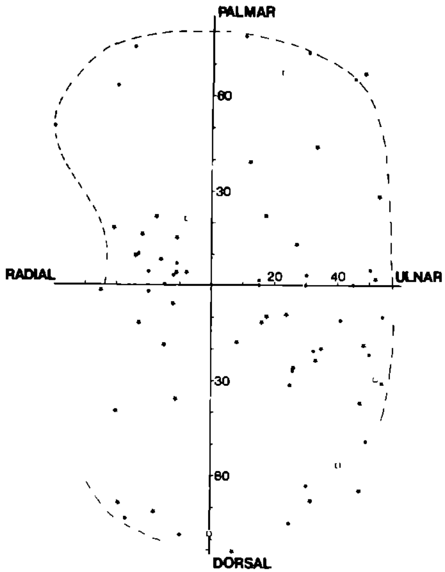


Figure 6.3 A projection of the 3D movement space of the hand on a transversal plane, showing the motions which are applied to the four specimens considered. The origin of the coordinate system represents the neutral position of the hand. The projection shows a kidney-shape movement range (✱: sample points of specimen 1; ●: specimen 2; □: specimen 3; ✧: specimen 4).

pro/supination) calculated for all sample points of the four specimens. These polynomials are presented in four sets of plots (Figures 6.4, 6.5, 6.6 and 6.7) for respectively the motions of the lunate, the capitate, the scaphoid and the trapezium relative to the fixed radius. The goodness of fit of these polynomials to the sample points, is a measure for the interspecimen reproducibility. The polynomials also enabled us to estimate Euler rotation angles for non-measured hand positions by interpolation. The polynomials calculated for the rotation angles of all sample points show acceptable fits. The r.m.s. values for the fits range between 4.5 and 14 degrees (Table 6.2).

The projections of the FHA's on transversal and frontal planes are shown for each carpal bone in separate figures (6.8A, B, C, D and E). Only the data of one wrist joint (specimen 1) are presented. These figures illustrate the dispersion of the FHA's around the pivot points and, visualize the closeness of the position vectors of the separate FHA's to the pivot point.

The directions of the FHA's as functions of the displacement of the hand are shown for each carpal in figures 6.9B, C, D, E and F. From these pictures the displacements of the carpals can be visualized best. In each figure the FHA data for all specimens considered are presented. In these figures a projection of the semispherical movement space of the hand on a transversal plane is given, with centrally, in the origin of the coordinate system, the representation of the neutral position. These figures furthermore contain arrows representing the direction of the FHA's and the amount of helical rotation about the FHA's. The starting-points of these arrows represent the movement, which is applied to the hand. The direction of an arrow represents the direction of the FHA, which describes the movement of the carpal induced by the movement of the hand from the neutral position to the position indicated by the starting-point. The lengths of the arrows indicate the amount of rotation. The pro/supination component in the direction of the FHA's is calculated, but for reasons of clearness it is neglected in the presentation, as it is in most cases far more smaller than the deviation and the flexion components of the movements. This can also be shown from the Euler rotation angle plots, which display rather flat polynomials for the pro/supination angles (Figures 6.4C, 6.5C, 6.6C and 6.7C). An example of how these figures (6.9B to F) should be interpreted is given in figure 6.9A: an arrow, starting in the fourth quadrant and directed parallel to the negative x-axis, represents a dorsal rotation combined with a radial translation of a carpal bone as the result of a ulnodorsal (fourth quadrant) rotational displacement of the hand.

The projections of the pivot points on frontal and transversal planes are given for each specimen in a separate figure (6.10). The positions and the projections of the pivot points relative to the positions and the projections of the markers in the bones were calculated. Combining the marker projections and the Röntgen images of the specimens resulted in the estimated positions of the pivot points relative to the bone geometry.

Carpal movements

When the directions of the finite helical axes of the carpal bones for the movement of the hand from the neutral position to different positions in the movement space of the hand are considered, it appears that the global behaviour of different carpals is not the same. Some of the carpals (capitate and trapezium) display motions rather similar to the applied displacement of the hand (Figures 6.9C and E). These carpals can be said to follow the movement of the hand very well. While the movements of other carpals tested (scaphoid and lunate) seem to be less proportional to the movements of the hand, and exhibit clear out-of-plane movements (Figures 6.9B and D).

Motions of carpal bones relative to the radius

In the following part the motions of each of the carpal bones relative to the radius will be discussed separately.

Lunate

All helical axes cross each other nearly in a fixed point relative to the laboratory coordinate system (Figure 6.8A). Hence, the lunate has an almost distinct pivot point. The distances between this point and the FHA's is on the average only 3 mm (Table 6.3). Hence, the positions of the helical axes hardly depend on the positions to which the hand is moved. The position of the pivot point appears to be in the distal half of the lunate for all four specimens, close to the articulation with the capitate, it varies somewhat in the ulnoradial direction over the specimens (Figures 6.10A to D). The directions of the helical axes for the lunate are influenced by the direction of the hand motion only to a small extent (Figure 6.9B). When the hand is moved from the neutral position to one of the dorsal quadrants, *viz.* the radiodorsal or the ulnodorsal quadrant, the helical axes are mainly radially directed, sometimes with a small dorsal component. This means that when the hand is moved to a position in one of these two quadrants the lunate rotates mainly dorsally and sometimes somewhat ulnarly. The translation of a carpal bone is parallel to the direction of the helical axis, in these cases (radiodorsal or ulnodorsal hand displacement) it was found to be radially. In the radiopalmar quadrant only small excursions were sampled. The main direction of the FHA's in this quadrant is ulnarly, indicating palmar flexion and ulnar translation of the lunate. In the ulnopalmar quadrant there is a gradual transition from ulnarly directed helical axes, when the hand is displaced palmarly to more radially and dorsally directed axes, when an ulnar motion is applied. On the radial border between the palmar quadrants and the dorsal ones the shift is very abrupt, from mainly radially to mainly ulnarly directed FHA's, or the other way around. In this range the movement of the lunate seems to be either palmar rotation, when the movement of the hand is radially and somewhat palmarly, or dorsal rotation when the hand is moved radially and somewhat dorsally. Hence, except for pure flexion movements of the hand, palmarly as well as dorsally, the rotations of the lunate can be said to be so-called out-of-plane motions (de Lange *et al.*, 1985). In the figures 6.9B to F out-of-plane motions are represented by arrows which are not perpendicular to the line connecting the neutral position with the starting-point of the arrow involved. The magnitude of the helical rotations of the lunate increases (maximally up to 50 degrees), when the applied hand movement is increased. The magnitude of rotation depends also on the direction of hand movement. When the hand is moved to positions into the ulndorsal quadrant, the rotations are higher than when

Table 6.2 The r.m.s. values for the fits of the polynomials to the Euler rotation angles (flexion, deviation and pro/supination) of the lunate, the capitate, the scaphoid and the trapezium.

	R.M.S. VALUES FOR POLYNOMIAL FIT		
	FLEXION	DEVIATION	PRO/SUP
LUNATE	9.2	7.2	5.8
CAPITATE	11	6.8	8.6
SCAPHOID	9.1	7.2	5
TRAPEZIUM	14	4.5	5.3

Table 6.3 The mean values and standard deviations of the dispersions of the FHA's (D) and of the angular dispersion around the pivot point (χ) for each of the carpal bones. The value n denotes the number of specimens over which these values could be determined.

	D	χ	n
LUNATE	2.8 ± 1.9	23.6 ± 3.7	4
CAPITATE	7.4 ± 7.7	34.1 ± 9.9	4
SCAPHOID	4.8 ± 4.2	20.9 ± 6.5	4
TRIQUETRUM	1.5	20.9	1
TRAPEZIUM	11.0 ± 5.0	45.8 ± 3.4	2

other motions are applied. The translations are greatest when the hand is moved to a position in the ulnodorsal quadrant (up to 2 mm) and smallest when a radiopalmarly directed displacement is applied.

Capitate

For the capitate the pivot point of the FHA's is somewhat more distally located in the wrist joint, than for the lunate. It is situated in the most proximal part of the capitate, close to the articulation with the lunate, it varies simultaneously with the pivot point of the lunate in the ulnoradial direction over the specimens (Figures 6.10A to D). The average dispersion between the FHA's near the pivot point is greater than that for the lunate, 7.5 mm (Table 6.3). The directions of the FHA's for the capitate are for all hand displacements more or less perpendicular to the directions of these displacements (Figure 6.9C). So, the rotations of the capitate resemble the movements of the hand; the capitate moves hardly out-of-plane. Only when the hand is moved to a position in the radiodorsal quadrant the FHA's are not fully perpendicular to the directions of the movements of the hand. When the hand is moved into this range the directions of the corresponding FHA's are somewhat more radially and less palmarly than would be expected due to perpendicularity. The amount of helical rotation is independent of the directions of the hand displacement, but varies positively with the amount of hand motion applied. Increased magnitudes of hand motion show increased helical rotations of the capitate, up to 85 degrees. The translations along the FHA's vary mainly with the direction of hand motion. The translations are distinctly larger (up to 6 mm) when the hand is moved into the ulnodorsal range, than when it is moved in other directions.

Scaphoid

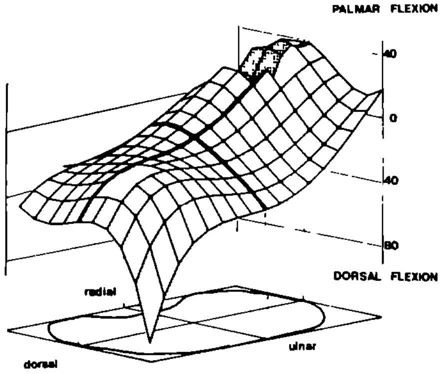
The FHA's for the scaphoids in three of the four specimens pass a point in the radial part of the articulation between lunate and capitate. In the fourth joint (specimen 3) it is located ulnarly in this articulation, in this specimen also the pivot points for capitate and lunate are found most ulnarly (Figures 6.10A to D). The dispersion around this pivot point is 5 mm on the average (Table 6.3). As for the lunate the direction of the motion of the scaphoid is affected only very little by the direction of hand motion. For this carpal bone the movement range can be subdivided into three parts, based on the main directions of the FHA's (Figure 6.9D). One of these consists of the two dorsal quadrants, the second one of the radiopalmar quadrant and the palmar half of the ulnopalmar quadrant and the third of the remaining part of the ulnopalmar quadrant. In the dorsal quadrants the helical axes are predominantly radially directed and to some extent dorsally, this means that the scaphoid will tilt dorsally and somewhat ulnarly, the helical translation is mainly radially and a little dorsally directed. In the radiopalmar and palmar part of the ulnopalmar quadrant the screw axes are ulnarly directed with a slight palmar component. Hence, the rotation of the scaphoid is palmarly and somewhat ulnarly. In the ulnar part of the ulnopalmar quadrant the displacements of the scaphoid change gradually between those observed in the dorsal quadrants and those found in the radiopalmar one. Both helical rotations and translations appear to vary with the amount of hand displacement. Translations and rotations are larger when the amount of displacement applied to the hand is increased. However the effect of increasing displacement on the helical translation is only minor. The helical rotations are also strongly affected by the direction of hand displacement, in the ulnodorsal quadrant the rotations are greatest. Maximally they are 75 degrees.

Trapezium

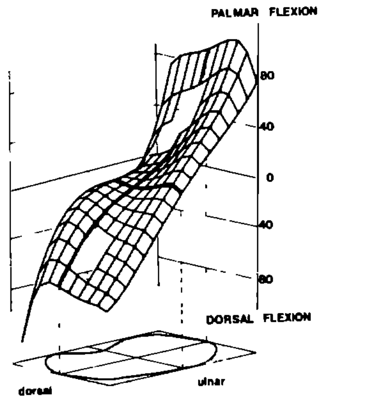
The trapezium has been considered in only two of the four specimens tested. The pivot point for the trapezium is located in the same region of the wrist joint as the pivots for the other carpals considered, close to the articulation between lunate, capitate and scaphoid. The dispersion of the FHA around the pivot point is larger than for the three other carpals, 11 mm (Table 6.3). The directions of the FHA's and so the directions of the

6.4 LUNATE relative to RADIUS

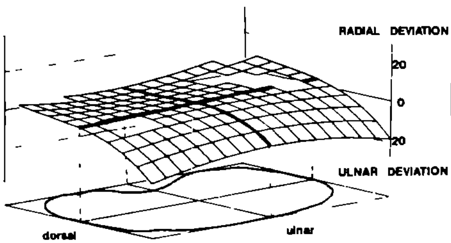
6.5 CAPITATE relative to RADIUS



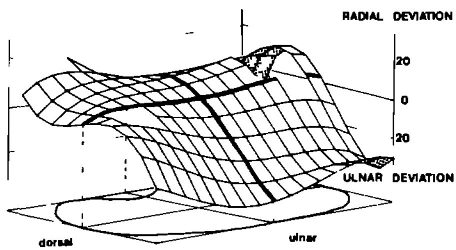
A



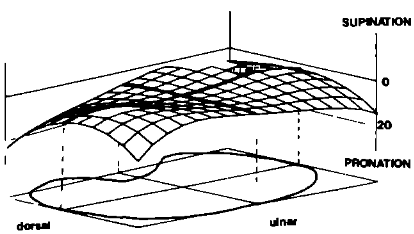
FLEXION ANGLE



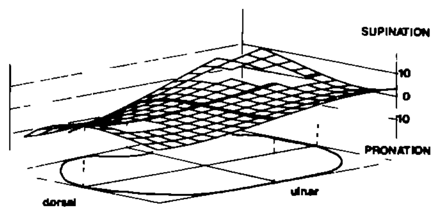
B



DEVIATION ANGLE



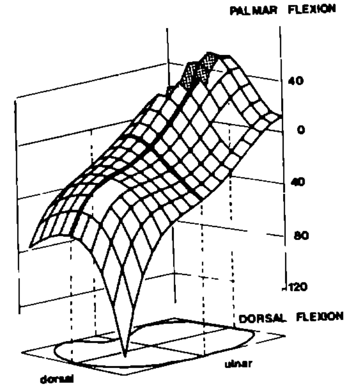
C



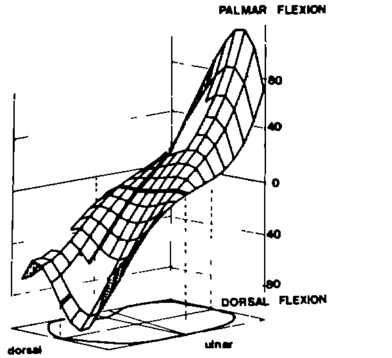
PRO/SUPINATION ANGLE

6.6 SCAPHOID relative to RADIUS

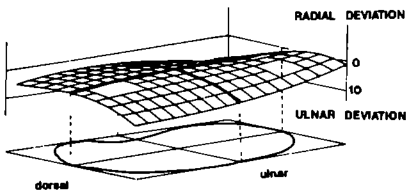
6.7 TRAPEZIUM relative to RADIUS



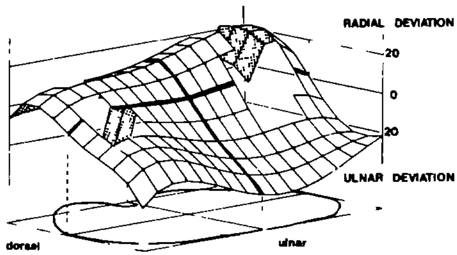
A



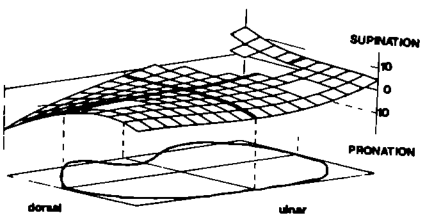
FLEXION ANGLE



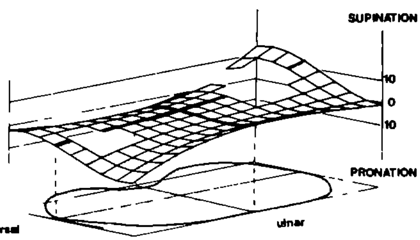
B



DEVIATION ANGLE



C



PRO/SUPINATION ANGLE

*Preceding pages: **Figures 6.4, 6.5, 6.6 and 6.7** The polynomial fits to the Euler rotation angles (vertical directions) for the carpal bones as a function of the 2D (deviation as well as flexion) movement of the hand (horizontal kidney-shape plane). The rotation angles for the lunate are given in figures 6.4A, B and C; those for the capitate in figures 6.5A, B and C, those for the scaphoid in figures 6.6A, B and C; those for the trapezium in figures 6.7A, B, and C. (A: rotation about the x-axis, representing flexion; B: rotation about the y-axis, representing deviation; C: rotation about the z-axis, representing pro/supination).*

movements of the trapezium are similar to those of the capitate (Figure 6.9E). For most hand displacements the corresponding FHA-directions are perpendicular to the displacements applied, indicating that the displacement of the trapezium is similar to the hand displacement. When the hand is moved into the radial quadrants, the angle between the line of hand displacement and the FHA is somewhat greater than 90 degrees, that means that when the hand is moved radially, the FHA is not exactly palmarly, but also a little radially directed, indicating a small out-of-plane motion. The amount of rotation about the FHA seems to be influenced only by the magnitude of the hand movement, increasing displacements correspond to larger rotations. The maximal rotation is about 80 degrees. The amount of translation is affected by the direction as well as the magnitude of the hand displacement. When the hand is moved ulnodorsally, greater translations, up to 9 mm, are observed, than during movements in other directions, where the maximally registered translations amount maximally 4 mm. Excursions of approximately 30 degrees result in the highest translations for each direction of hand movement both smaller and larger excursions result in smaller helical translations.

Triquetrum

The movements of the triquetrum are considered in only one specimen. In this joint only movement possibilities of the hand into the ulnodorsal quadrant are taken into account. The position of the pivot point for this specimen is located in the radiodistal part of the lunate, so in the same region of the wrist joint as the pivots of the other carpals. The directions of the FHA's and the rotations and translations resemble those of the other carpals of the proximal row, the lunate and the scaphoid (Figure 6.9F).

Motions of carpal bones relative to neighbouring carpals

When the hand is moved into an ulnar direction (ulnopalmar of ulnodorsal) the FHA's for the movement of trapezium relatively to scaphoid are ulnodorsally directed, indicating that relative to the scaphoid the trapezium rotates ulnopalmarly and translates in the ulnodorsal directions. When the hand is moved into one of the radial quadrants, the motions of the trapezium relative to the scaphoid are opposite, the FHA's are radiopalmarly directed. Relatively to the lunate the capitate rotates mainly palmarly and translates ulnarly, when the hand is moved into the ulnopalmar quadrant. During displacements of the hand into the radiodorsal directions, opposite motion occur. During ulnodorsal displacements of the hand the FHA's are mainly dorsally directed and during radiopalmar motions they point mainly palmarly, the movements of the capitate are then respectively ulnar rotation and dorsal translation and radial rotation and palmar translation. The movements between the carpals of the same row are less distinct than those between different rows. The amounts of helical rotation and translation are much smaller. Between capitate and trapezium merely small pro/supination motions occur. Relative to the lunate the scaphoid rotates more dorsally when the hand is moved in one of both dorsal quadrants (radiodorsal and ulnodorsal). *During displacements into the palmar quadrants only slight* relative motions between lunate and scaphoid are observed.

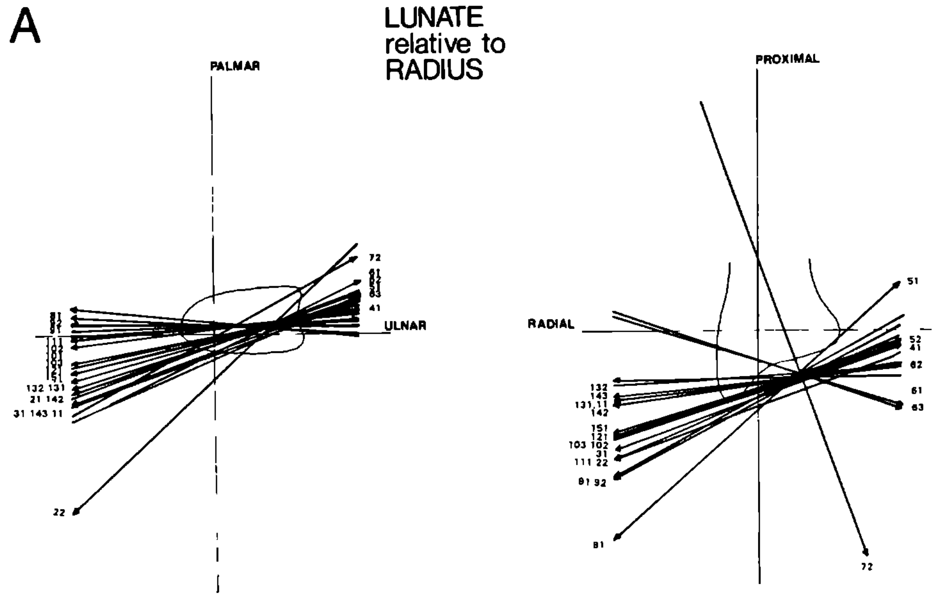
Ligament length changes

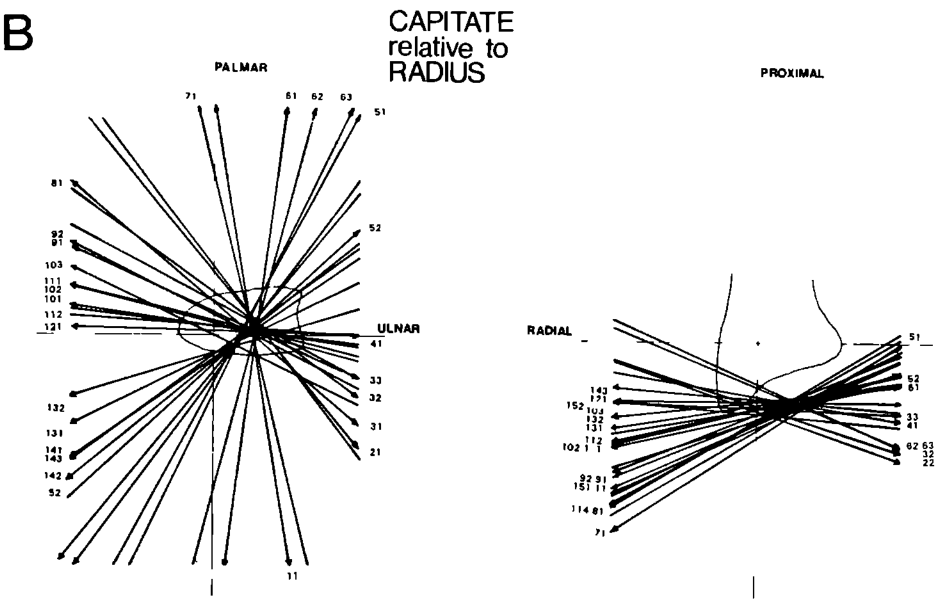
The relative length changes of the ligaments vary proportionally to the amount of excursion of the hand. In none of the ligaments tested the length changes exceeded those found during maximal pure deviation or flexion movements of the hand.

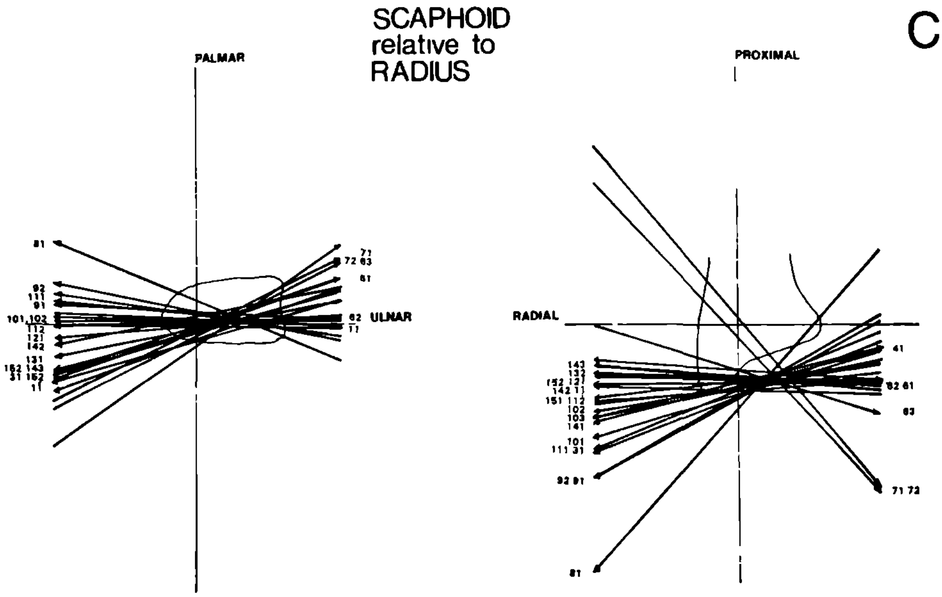
For the RCP ligament sufficient data could be collected only in the ulnodorsal and the radiopalmar quadrants. The RCP ligament is lengthened when the hand is moved into the ulnodorsal quadrant. Over the specimens the maximal elongations vary between 10 and 14% relative to the lengths in the neutral position. No effect of the direction of the hand motion on the lengthening is found. When the hand is moved in a palmar direction the ligament length decreases.

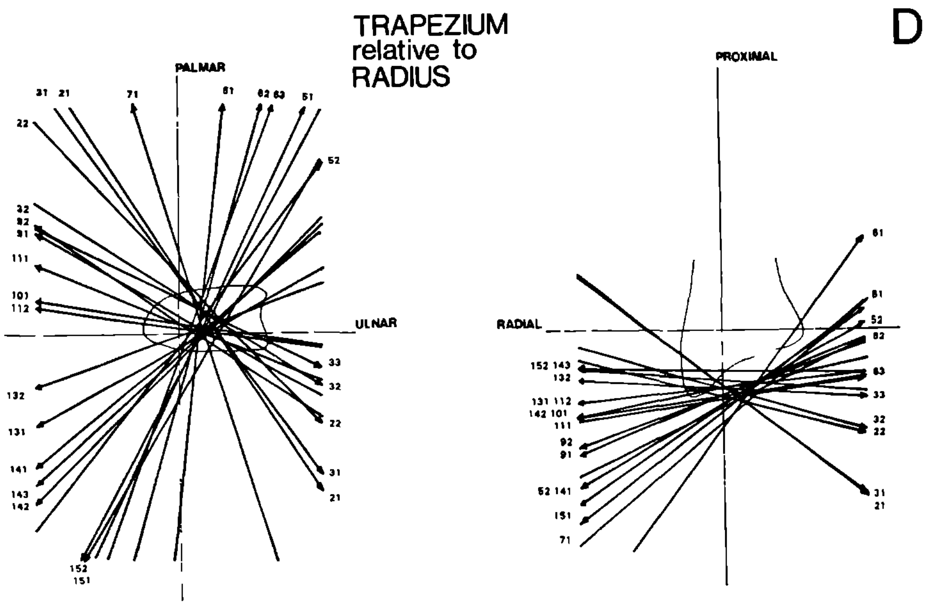
The proximal string of the RLP ligament was sampled in four specimens while the hand is displaced ulnodorsally or radiopalmarly, in one specimen measurements could be carried out when an radiodorsal motion is applied to the hand. During motions into the ulnodorsal and radiodorsal quadrant the ligament string is elongated, maximally 7.5 to 11%. Radiopalmar motions of the hand lead to shortening of the ligament.

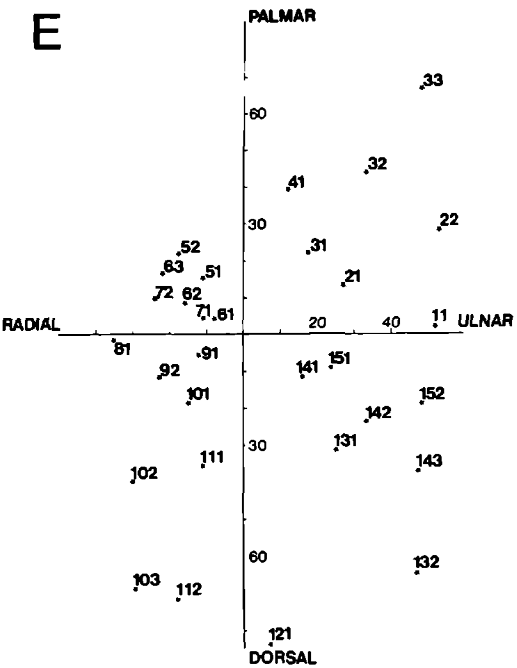
The distal string of the RLP ligament is sufficiently sampled for ulnodorsal and radiopalmar motions of the hand. During radiodorsal


A
LUNATE relative to RADIUS
PALMAR
ULNAR
PROXIMAL
RADIAL


B
CAPITATE relative to RADIUS
PALMAR
ULNAR
PROXIMAL
RADIAL


SCAPHOID
relative to
RADIUS
C
PALMAR
ULNAR
PROXIMAL
RADIAL


TRAPEZIUM
relative to
RADIUS
D
PALMAR
ULNAR
PROXIMAL
RADIAL

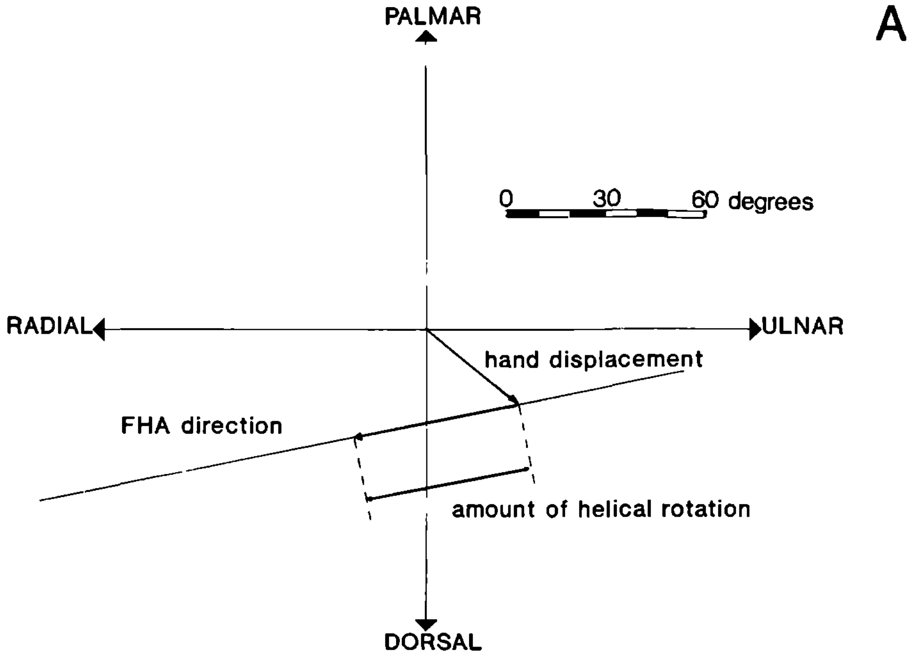


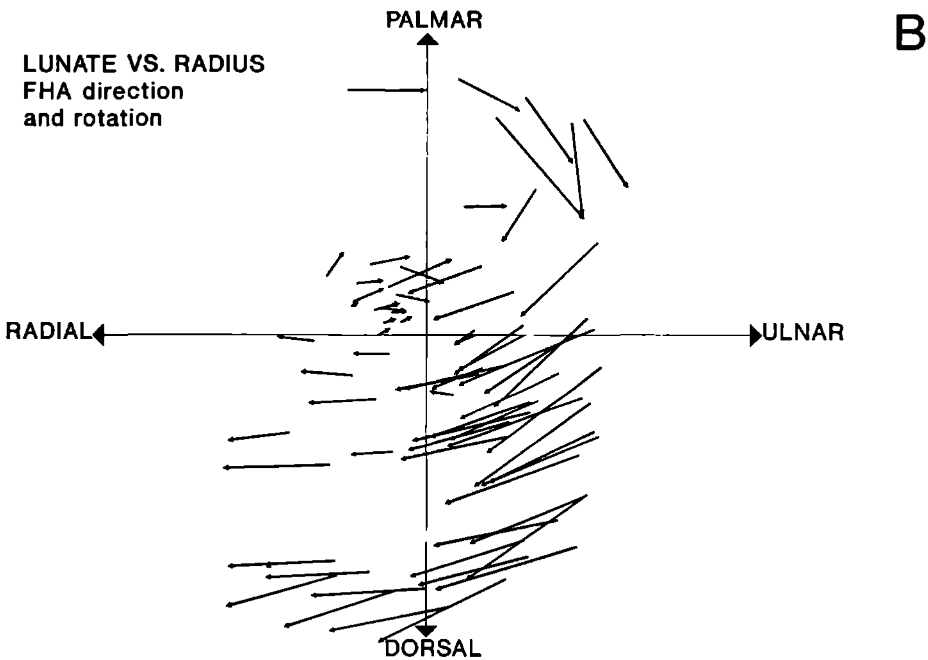
Preceding pages: ***Figure 6.8*** *The projections of the bundles of FHA's for the movements of the carpal bones relative to the radius on a transversal plane* ***(left)*** *and a frontal one* ***(right)****. The numbers near the projections of the FHA's correspond to the numbers in the kidney-shape projection of the hand motion, indicating the movement of the hand from the neutral position to the point where the number is located. The FHA's shown are the data for specimen 1 (8A: lunate; 8B: capitate; 8C: scaphoid; 8D: trapezium). The numbers near the FHA's correspond to the numbers in figure 8E, denoting the displacement of the hand.*

movements determinations were carried out in only two specimens. For ulnodorsal, radiodorsal and radiopalmar movements of the hand the length-change patterns for the RLPd ligament qualitatively resemble those for the RLPp ligament. However, quantitatively, the elongations of the RLPd ligaments are greater, during maximal excursions the relative elongations range between 7 and 14% for different specimens.

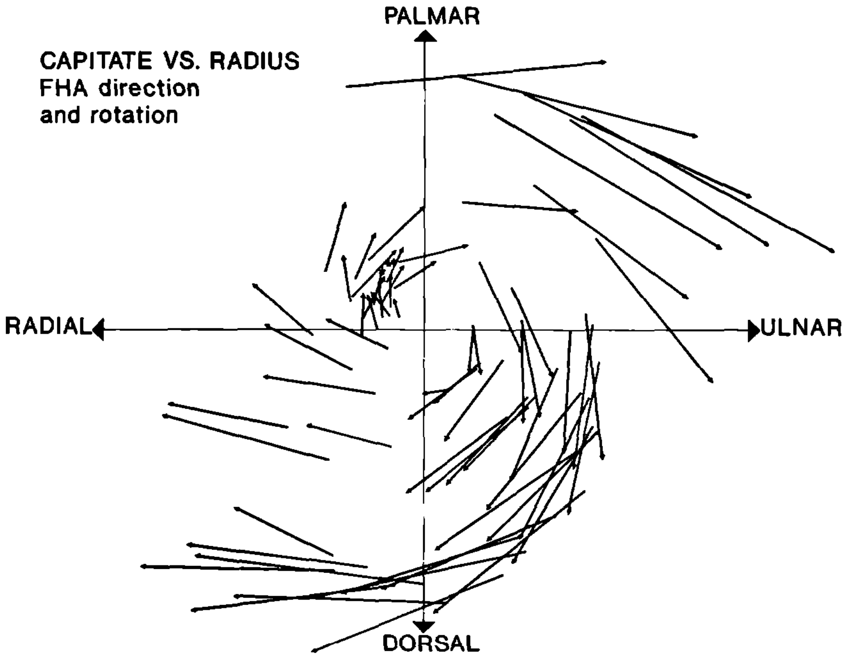
For the RTD ligament only the lengths during ulnodorsal and radiopalmar displacements of the hand are available. In one of these specimens also an ulnopalmar displacement could be measured. These data show shortening of the ligament when the hand is moved into the ulnodorsal quadrant and lengthening when a radiopalmar displacement is applied, maximally 10%.

The TTD ligament, for which only data of 3 specimens during ulnodorsal and of two specimens during radiopalmar hand displacements are available, becomes elongated when the hand is moved ulnarly. Radiopalmar displacement leads to shortening of the ligament.

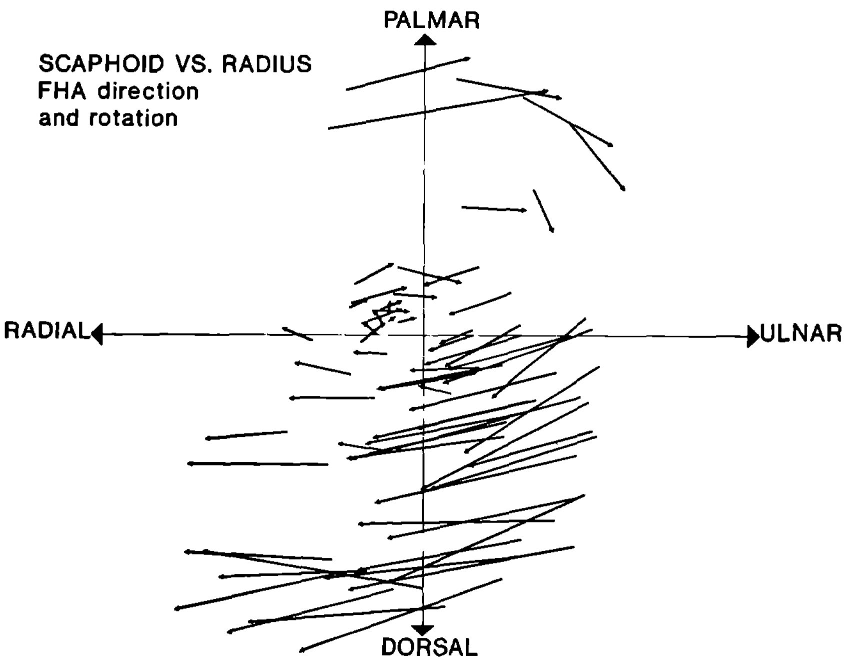

A
PALMAR
0
30
60 degrees
RADIAL
ULNAR
hand displacement
FHA direction
amount of helical rotation
DORSAL

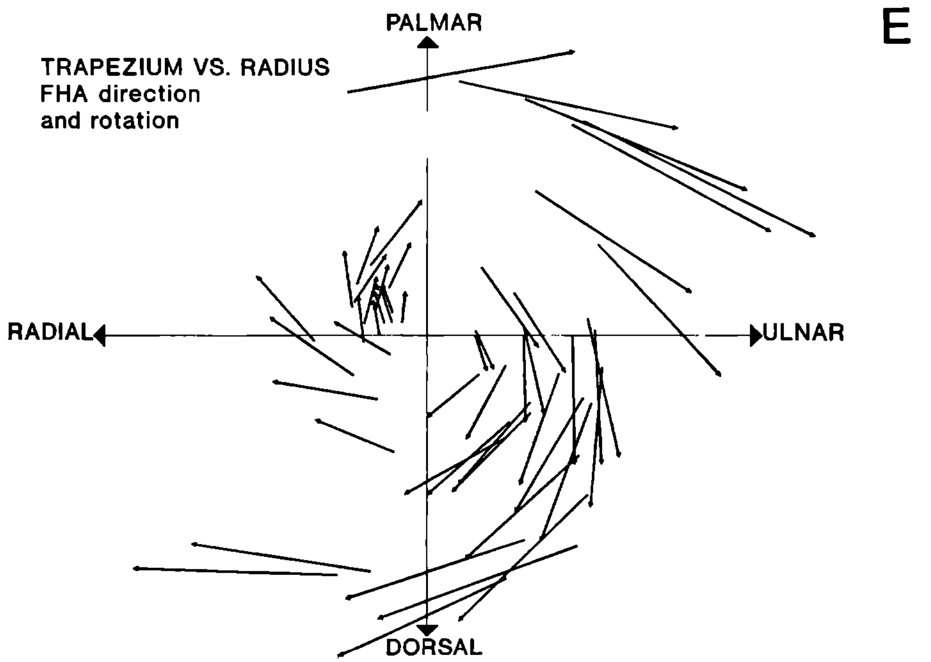

B
PALMAR
LUNATE VS. RADIUS
FHA direction
and rotation
RADIAL
ULNAR
DORSAL

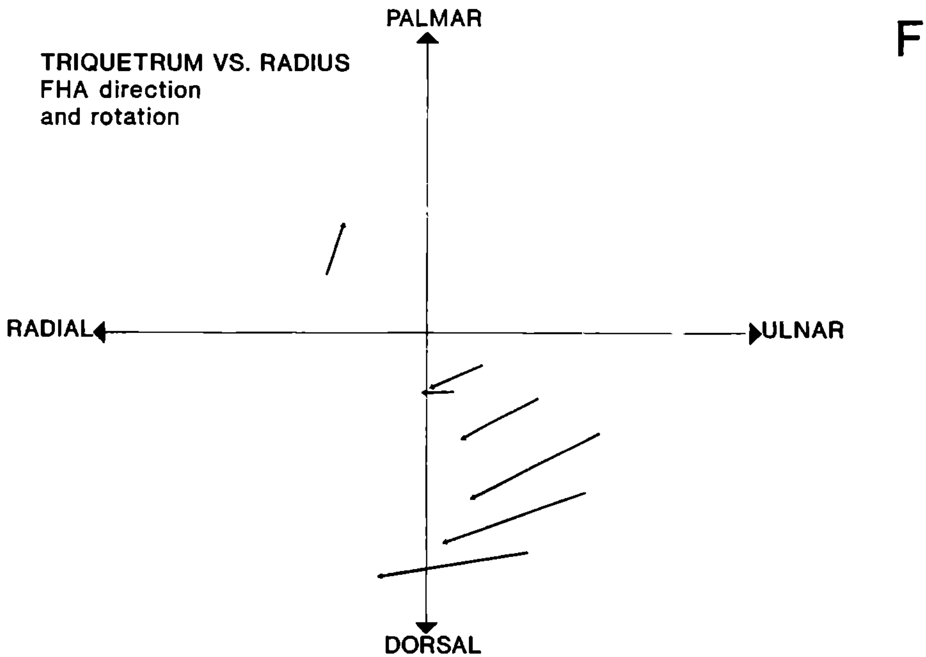
C


CAPITATE VS. RADIUS
FHA direction
and rotation
PALMAR
RADIAL
ULNAR
DORSAL

D


SCAPHOID VS. RADIUS
FHA direction
and rotation
PALMAR
RADIAL
ULNAR
DORSAL


E
TRAPEZIUM VS. RADIUS
FHA direction
and rotation
PALMAR
RADIAL
ULNAR
DORSAL


F
TRIQUETRUM VS. RADIUS
FHA direction
and rotation
PALMAR
RADIAL
ULNAR
DORSAL

Preceding pages: ***Figure 6.9*** *The directions of the FHA's and the amount of helical rotation for the movement of each of the carpals relative to the radius as a function of hand displacement. The origin of the coordinate system represents the neutral position of the hand. The starting-points of the arrows represent the movements of the hand relative to the neutral position. The directions of the arrows resemble the directions of the FHA's, the lengths of the arrows correspond to the amounts of helical rotations. The arrows which are in fact 3-dimensional are projected on a transversal plane, neglecting the pro/supination component of the FHA's. (**6.9B**: lunate; **6.9C**: capitate; **6.9D**: scaphoid; **6.9E**: trapezium; **6.9F**: triquetrum). Figure **6.9A** shows how to interpret these figures.*

DISCUSSION

Woltring *et al.* (1985) showed that the accuracy of helical axis parameters depends on the amount of rotation about and the translation along the helical axis, the number and the distribution of the markers in a bone and the spatial configuration of the markers. De Lange *et al.* (1990b) showed experimentally that Woltring's error model is valid for the wrist joint. They also found that the determination of the FHA parameters can be done accurately. As in our study the magnitudes of the variables which determine the accuracy are similar to those used by de Lange et al. (1990b), it should be concluded that the representation of the carpal movements by helical axes was accurate in this study.

It has been shown in earlier studies (de Lange *et al.* 1990c; Savelberg *et al.*, 1991) that the method of presenting ligament fibres by a string of radio-opaque markers is accurate for the determination of the ligament length change. The problem, which emerged from the present experiments is that, due to longitudinal rotations of the specimens relatively to the x-ray film cassette and the Röntgen tubes, the simultaneous representation of many ligaments in a joint interferes with the recognition of the markers. Therefore in future experiments, it should be chosen to represent only a few ligaments at a time, or to consider the possibility of different-sized markers for different ligaments.

Since this study is unique in determining carpal motion during full range movements of the hand it is not possible to compare the present results to those of similar studies. But those results from the present study which represent pure flexion or pure deviation motions can of course be compared to former studies on carpal motions during flexion and deviation of the hand. In the plots of the polynomial fits to the Euler rotation angles, the data representing pure flexion and pure deviation are presented by bold lines, facilitating this comparison (Figures 6.4, 6.5, 6.6 and 6.7). The patterns of those bold lines appear to resemble the kinematic data presented by de

Lange *et al.* (1985) well. For example, in figure 6.4A the bold line representing pure flexion of the hand shows increasing palmar flexion of the lunate to about 40 degrees when the hand is flexed palmarly and also 40 degrees of dorsal flexion when the hand is flexed dorsally. Furthermore the bold line representing pure deviation of the hand shows some 40 degrees of dorsal flexion of the lunate during ulnar deviation and hardly any flexion movement during radial deviation.

These data agree well with the Euler flexion angles for the lunate presented by de Lange *et al.* (1985). Also for the helical axes data these kinds of agreements to former studies (Berger *et al.*, 1982; de Lange, 1987; Ruby *et al.*, 1988; Savelberg *et al.*, 1991) can be shown.

Both qualitatively and quantitatively, evidence exists in the FHA data that the kinematic parameters determined for the first specimen, in which the full range of wrist-joint motion has been sampled, may be considered as reliable values

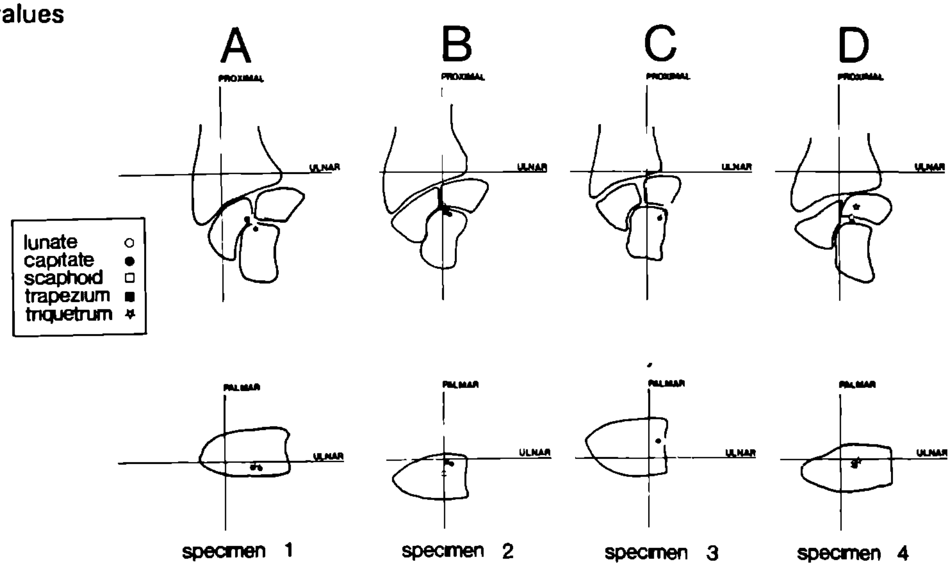


Figure 6.10 The positions of the pivot points of the carpal bones for movements relative to the radius for each of the four specimens tested (A: specimen 1; B: specimen 2; C: specimen 3; D: specimen 4).

and that they may be generalized to other wrist joints. The clear reproducibility over the specimens for those parts of the range of wrist-joint motion, which have been determined in all four specimens, the ulnodorsal range (Figures 6.9), and the good fit of the present data to those of studies of pure flexion or deviation motions of the hand (Berger *et al.*, 1982; de Lange *et al.*, 1985; de Lange, 1987; Ruby *et al.*, 1988; Savelberg *et al.*, 1991) should be considered as qualitative indications for interspecimen reproducibility of the data. Quantitatively, this is substantiated by the good fit of the polynomials to the Euler rotation angles (Table 6.2 and Figures 6.4, 6.5, 6.6 and 6.7).

When the data are considered, two ever-occurring phenomena appear, which have also been shown in former studies for pure flexion and pure deviation of the wrist joint (Berger *et al.*, 1982; de Lange *et al.*, 1985; de Lange, 1987 Ruby *et al.*, 1988). A distinct difference is found between the movement of the carpals of the proximal row and those of the distal row. Secondly, within the rows of carpal bones, it can be noticed that both distal carpals behave very similarly, while within the proximal row the carpal motions are equally directed, but have varying magnitudes. The differences between both rows of carpals are most clearly expressed by the differences in the directions of the FHA's. The patterns of figures 6.9B and D (lunate and scaphoid) on the one side and those of figures 6.9C and E (capitate and trapezium) on the other hand are very different, but mutually similar. Also the transversal projections of the FHA's in figures 6.8A to D indicate this distinction between the carpals of the proximal and the distal row.

The positions of the pivot points are very similar to those for pure flexion and pure deviation experiments reported by de Lange (1987). Also between the four specimens, which represent experiments with different motions applied, the resemblance of the pivot-point positions is great. These facts suggest that the position of the pivot point is not determined by the motion applied to the hand, but that it is mainly dependent on the geometry of the specimen.

The motions of lunate and scaphoid as displayed in these experiments are unique. They have not been shown before, neither could these motions reasonably be predicted from pure flexion and deviation studies. These carpals exhibit 'out-of-plane' rotations during the greater part of hand motions (de Lange, 1987). Only when pure palmar or dorsal flexion is applied to the hand the displacements of these two carpals are similar to the displacement of the hand. In all other directions of hand movements distinct differences occur between the directions of hand motions and those of lunate and scaphoid, respectively. From the present data it can be suggested that whereas the movements of the capitate and trapezium seem to be proportionally to the movements of the hand, the motions of the lunate and the scaphoid are not subject to such a relationship. Hence, the concept of the carpal mechanism, which considers the proximal row of carpals as a segment, which adjusts its geometry to the radius and to the distal row, and which position depends on the position assumed by the wrist joint (de Lange, 1987; Ruby *et al.*, 1988), might be of interest here.

Also the data for the helical rotations and translations, which have been determined in this study are unique. It appeared that the amount of helical rotation and translation depends not only on the magnitude of the displacement applied to the hand, but for some carpals the amounts of helical rotation and translation are also influenced by the direction of the motion pathway. Especially when the hand is moved into the ulnodorsal quadrant the helical rotations of lunate and scaphoid are found to be higher than when the hand is displaced along motion pathways into other quadrants. For all four bones considered the helical translations seem to be greater when an ulnodorsal motion is applied than when the joint is subjected to displacements into other directions. This knowledge is not only of importance to understand the actual displacement of the carpal bones from the FHA data, but also, as the elongations of the ligaments depend on the amount of carpal displacement, to be able to understand the length changes of the ligaments as a function of hand movement, that is carpal bone motions. Within this context it should be noted that the effects of helical rotation and translation on the ligaments are by definition differently directed. For example, if a helical axis is dorsally directed, the rotation is ulnarly, while the translation is dorsally. This means that the effects of helical rotations and translations on a carpal ligament can amplify or neutralize each other. Hence, to understand the actual motions that occur within the joint and the effects these motions have on ligaments not only the helical directions should be considered, but also the mutual proportions of helical rotations and translations.

Those ligament length changes, which could be determined in these experiments, are in accord with the carpal movements and also with the length changes measured during pure flexion and pure deviation studies (de Lange *et al.*, 1990c; Savelberg *et al.*, 1991). No evidence has been found that during combined flexion and deviation movements of the hand greater strains are applied to the wrist-joint ligaments than during pure flexion or pure deviation. The results suggest that in the parts of the range of motion regarded in the experiments the loadability of the ligaments is not fully utilized. Unfortunately these determinations were not successful for all ligaments. It was also not possible to cover the whole movement range of the hand.

In comparison with pure flexion and pure deviation studies, the determinations which are carried out in this study during combined flexion and deviation movements of the hand, extend our knowledge on carpal kinematics and on ligament behaviour. Not only the quantitative aspect of an enlarged set of available data is a benefit of this study, but also the web of sample points in the full range of wrist-joint motion has been extended so that new phenomena have become clear, and already known features have been confirmed for the full range. It is concluded from this study that the carpal movements in the ulnodorsal range of the hand motion are much more pronounced than those in other ranges. It is also shown that a clear distinction exists between the behaviour of the proximal and the distal row. This was already shown in pure flexion and deviation studies, but can now be said to hold for the full range of wrist-joint motion. The distal row might functionally be considered as a part of the metacarpals, while it might be concluded from this study that understanding the form-function relationship of the proximal row will be the key to understanding the morphology of the wrist joint. Furthermore, it should be concluded that the so-called main axes of carpal motion, flexion and deviation, are merely samples of a much wider range of possible directions of hand displacements.

FINAL CONSIDERATIONS

REVIEW OF THE RESULTS

In the introduction it has been argued that the main topics of this study are the determination of forces in carpal ligaments and the assessment of the kinematic behaviour of the carpal system during motions of the hand in the total envelope of wrist-joint movements. It is stated that ligaments are generally considered to be able to transmit forces. Consequently the movements of the carpal bones during motions of the hand might be affected by forces transmitted by ligaments. De Lange (1987) and de Lange *et al.* (1990c) showed that some ligaments elongate considerably and therefore might transmit forces. The present study attempts to investigate whether these elongation are accompanied by force transmission and to investigate all possible ligament length changes. It is reasoned that it is of interest to obtain knowledge of the carpal ligament force patterns, as well as of the simultaneously occurring movements of the carpal bones, as the force patterns will render insight in the significance of the ligaments for the carpal mechanism.

The choice for the second point of interest of this study, the analysis of the wrist-joint behaviour during motions of the joint, other than pure flexion or deviation, is rationalized by stating that the commonly analysed motions represent only partly movements required during activities of daily living. Hence, it can be questioned whether those motions defined by anatomists and biomechanists will give complete insight in the joint functioning.

In this project the first of these two questions is elaborated in a flow of four subsequent chapters and studies. Respectively, ligament lengthening and carpal kinematics as a function of hand motion and ligament material properties are studied, a method to determine length changes and material properties in the same specimen and to relate both parameters to each other is developed, and finally ligament force patterns are determined by combining techniques developed and knowledge obtained in the foregoing parts. The second major question is considered in a final set of experiments.

REVIEW OF RESULTS BY CHAPTER

In the second chapter of this thesis, *Human Carpal Ligament Recruitment and Three-Dimensional Carpal Motion*, the length changes of carpal ligaments are the object of study. The amount of ligament length changes during flexion and deviation of the hand is assessed, as are the mechanisms underlying ligament lengthening, and the effects of hand motions on different ligament fibres classified as belonging to the same ligament. It can be shown that the doubts about current concepts on ligament length change (Mayfield *et al.*, 1976; Bonjean *et al.*, 1981; Taleisnik, 1985), which are raised from 3D carpal kinematic analyses (De Lange *et al.*, 1985, Ruby *et al.*, 1988), are justified. Furthermore, it is found that different fibres of a ligament can be elongated differently. From this it is deduced that the ligament should not be considered as the functional entity, but that rather the behaviour of ligament fibres have to be the object of experimentation. The analysis of the mechanisms underlying elongation teaches that not only the displacement of the bones to which a ligament inserts can cause change of length, but that also the movement of carpals, which a ligament crosses, can affect the length of a ligament. The 3-dimensional aspect of the movement of the carpals is shown to be essential to understand the length change of the ligaments properly.

The third chapter, *Stiffness of the Ligaments of the Human Wrist Joint*, is about the material properties of selected carpal ligaments. The relevance of this part of the study is in the development of a technique to carry out tensile tests on relatively small carpal ligaments and in the mere documentation of the tangent moduli of these structures, which are unknown. It is found that some ligaments have significantly larger tangent moduli than others. However, attempts to connect these different moduli to functions of the ligaments remain unfruitful.

In the fourth chapter, *Effects of Preconditioning on Wrist-Joint Ligament Forces; Estimates with an Indirect Measurement Method for Joint Specimens*, a method to estimate ligament forces is presented. It is shown that the accuracy of the method is good, but that the outcomes are susceptible to preconditioning of the tissue. The contents of this chapter are not only highly important to this thesis, but are also significant to testing of other soft-tissue structures.

In the fifth chapter, *Strains and Forces in Selected Carpal Ligaments during* In-Vitro *Flexion and Deviation Movements of the Hand*, the methods developed in the previous chapters are combined to determine the forces which are transmitted by carpal ligaments during flexion and deviation movements of the hand. It is questioned what the contribution of ligament forces to the kinematic behaviour of the joint is. The main conclusion from these experiments is that this contribution, at least in cadaver specimens, cannot be of great importance. Although the general trends in the strain and force patterns are reproducible, it is shown that the absolute values of the force patterns of different specimens vary widely. It is unlikely that these force patterns are responsible for the movements of the carpal bones, which are found to be very consistent over the specimens. Hence, concepts of the wrist-joint mechanism which ascribe a major role to ligament functioning in controlling carpal motion, and treatments of carpal injuries, which interfere with ligaments, are not supported by this study.

Finally, in the sixth chapter, *Carpal Bone Kinematics and Ligament Lengthening Studied in the Total Envelope of Joint Movement*, the scope of study is enlarged from phenomena occurring during only pure flexion and deviation of the wrist-joint to the joint behaviour during motions covering the full envelope of hand motion. Not only are these features documented aiming at more extended concepts of the mechanism, but also specific questions are addressed. It is investigated whether the ligaments, which during pure flexion and pure deviation seem to be loaded only moderately (chapter 5), are addressed more extremely. It is found, also in these experiments, simulating the movements of daily living more closely, that the length changes in the ligaments do not exceed the elongations found during maximal excursions in straight flexion and deviation about the main axes of the joint. The data on the carpal kinematics confirm the notion raised from 3-D experimental investigations of carpal kinematics during flexion and deviation, that the distal row behaves like the metacarpals and that the proximal one adjusts its position to the distal one and the radius. From this it has been suggested that for the understanding of the carpal mechanism it will be most important to judge the role of the proximal row of carpals properly. Since the distal row appears to follow the movements of the hand, it might be considered more as a part of the hand, hence rather belonging to the system which has to be positioned by the wrist-joint relative to the forearm, than as a part of the carpal joint itself. From the specific data on the carpal kinematics it has been concluded that flexion and deviation, the movements about the so-called main axes of wrist-joint motion, are only examples of possible hand displacements.

In summary the answers to the major questions of this study are:

- The forces which are transmitted by ligaments during movements of the hand relatively to the forearm do not play a major part in the motions of the wrist joint.
- The features found in straight flexion and deviation experiments do not characterize the mechanism of the wrist joint satisfactorily.

IMPLICATIONS OF THE RESULTS

Implications for the medical practice

The aim of this study is not only to contribute to the fundamental understanding of a part of the musculoskeletal apparatus, but also to add information which will help hand surgeons in the treatment of wrist-joint problems. In treatment of wrist-joint injuries and instabilities it is common to apply limited arthrodeses to carpal joints, several carpal bones are rigidly connected to each other or to the radius (Watson, 1980). These arthrodeses are always accompanied by a certain loss of movability in the joint. The amount of this loss is dependent on the kind of arthrodesis applied.

When we extrapolate the findings of this study concerning the carpal kinematics during full envelope movements (chapter 6) to predictions for the movability remaining after limited carpal arthrodeses are applied, it might be hypothesized that the limitations of the movability of the hand will be greatest when carpal bones of the proximal and the distal row are fused (*e.g.* scaphoid-trapezium-trapezoid, scaphoid-capitate, hamate-triquetrum or lunate-capitate). Fusions of carpals belonging to the same row can be expected to hamper the movements of the hand less. The experiments on full envelope movement kinematics have shown that the motion patterns of carpals of the same row differ only quantitatively, their amount of motion is not always equal, but the directions into which they move are always the same. When carpals of different rows are considered, it is noticed that they differ also qualitatively, not even their directions of movement are similar. The only exception to this is flexion of the hand. In that case all carpals, those of the proximal as well as those of the distal row, move in the same direction.

Studies on the limitations of movability induced by arthrodeses applied to joint specimens, consider only flexion and deviation movements of the hand (Douglas *et al.*, 1987; Gellman *et al.*, 1988; Garcia-Elias *et al.*, 1989). These authors report that the largest limitations of movability occur during deviation of the hand, and in cases where carpals of different rows are fused. Flexion movements are found to hamper the movements of the hand hardly. but this thesis shows that flexion movement is not representative for the movements of the hand, rather it represents an exception to the rule that carpals of different rows move into different directions during movements of the hand. Most hand motions required during activities of daily living are accompanied by opposite motions of carpals belonging to different rows. Therefore, when evaluating the effects of limited arthrodeses on the amount of movability retained, not only the deviation and the non-representative flexion motion should be considered. In general it can be argued, that concerning the effects on movability of the hand, fusions crossing the midcarpal joint should be avoided as much as possible.

Theoretical considerations of the results

An aspect of the ligaments which is cleared in this study is the relationship between elongation of a ligament fibre and on the one hand the displacement of the carpals to which the fibre is connected and on the other the position of the fibre relative to the carpals. The amount of elongation of a fibre is dependent on the position of that fibre, given the displacement of the carpals to which it is connected.

From the fact that different elongations are found for different fibres within the same ligament (chapter 2), the conclusion is drawn that each fibre, or at least each group of fibres in the ligament, will have a different function. Therefore, the notion of a ligament should not exceed the anatomical one: a number of connective tissue fibres running between the same bony structures. For functional analyses of the connective tissue structures the focus should be the level of the fibres. Therefore, a more thorough analysis of the different behaviour of different fibres or different groups of fibres should be recommended as one of the major items for future research.

In the introduction to this thesis it is argued that with the knowledge of the forces transmitted by ligaments we are able to understand the forms of the ligaments, their position and material properties, and that we get insight in the joint mechanism. The conclusion from this thesis conceming the forces transmitted by ligaments is, that, at least in cadaver specimens, the quantitative values of these forces do not display a systematic, reproducible relationship with the movements of the carpals. Consequently, it is found reasonable to conclude that the force transmission through the carpal bones, via the articulation surfaces, is much more effective for the control of carpal motions than that through the ligaments. However, this does not necessarily imply that ligament forces can be neglected. In current literature two notions on wrist-joint ligament function are common, the one stating that ligaments control carpal motion, the other assuming that ligaments fulfil a significant role in maintaining the integrity of the joint. The first notion is not supported by the results of the present study. The trends in the force patterns, which are found to be reproducible over the specimens, show increasing forces when the endpositions of movements are approached. In these cases forces are estimated amounting up to 60 N, which is still considerable. Hence, it is reasonable to suggest that preventing disintegration of the wrist joint is a major role of carpal ligaments. The control of the movements of the carpals during normal, physiological movements of the hand should be considered as taken care of by the geometry of the carpal bones or the small interosseous ligaments, which are not studied in this project.

Current thinking about the wrist-joint mechanism is dominated by two concepts, the concept of the fixed horizontal rows (Mayfield *et al.*, 1976; Volz *et al.*, 1980; Youm and Flatt, 1980; Bonjean *et al.*, 1981) and the concept of interactive longitudinal columns, the carpal-link concept (Gilford *et al.*, 1943; Linscheid *et al.*, 1972; Kauer, 1974, 1986; Taleisnik, 1976; Weber, 1984; Kauer and de Lange, 1987; Kuhlmann and Tubiana, 1988). Both concepts are used to motivate surgical treatments and classifications of instabilities and diagnoses, and deduce the role of ligaments for the mechanism. However, the problem with both concepts is that they are based on carpal motions observed from 2D Röntgenograms, that they are descriptive but many times used as if they had explaining power, that the criterion for classification is anatomical rather than functional and that assumptions on carpal tendencies are made which are not verified. From the experimentations on the total envelope of wrist joint movements it appears that neither of the descriptions hold. Neither the carpals move in two separable rows around a fixed centre of rotation, nor is evidence found to support a vertical, column-like arrangement. For flexion and deviation movements of the hand this has already been shown by de Lange (1987) and Ruby *et al.* (1988). Both come to the conclusion that something like a modified fixed row concept, without a fixed centre of rotation around which both rows are thought to rotate, and without a fixed, but rather with an adjustable proximal row will describe the motions of the carpals best. Hence, the carpal joint can be described as a system consisting of the radius and the ulnar articular disc, the hand including all structures distal from the midcarpal joint and one row of carpal bones, *i.e.* the scaphoid, the lunate and the triquetrum. To model this system it can be thought of as consisting of three segments, two relatively rigid and one deformable. The deformable one consists of the row of proximal carpals, and can be adjusted to the space left by both other segments, the forearm and the hand. The deformation of the proximal row and positioning of its carpals is controlled by the forces transmitted by the ligaments and the articular surfaces. The directions and magnitudes of these forces are determined by the morphology of the joint. The origin of these forces is in the muscular or external forces, which are needed to position the hand relative to the forearm.

In the introduction it is argued that this project should contribute to models of the joint, which have explanatory power, and not just describe structures and phenomena. This thesis was indeed also descriptive: I did not determine any causal relationship between forms and functions, though it contributed to understanding the morphology of the joint. The description is needed to learn what seems to be important, intending to limit the information a model should comprise. It is argued based on that description that the joint should be considered as a set of physical rules (ligament forces and carpal contact forces) which determine the position of the hand relative to the forearm by controlling the position of the proximal row of carpals. Hence, the total system, with which this project started, has been reduced to these aspects, which really seem to matter. Furthermore, the number of physical rules has been limited. Evidence has been presented to state that the ligaments considered in the present study (although more study is needed to prove that this holds for all fibre bundles in the ligaments), do not comprise an important part of the rules, but the geometry of a limited number of carpals and interosseous ligaments should be considered further.

Future research should focus on the forces which determine the relationship between the form and position of the proximal row of carpal bones and the position of the hand relative to the forearm. It can be expected that the force transmission by carpal geometry and interosseous ligaments will be of interest, but also a sophisticated model of the ligaments measured in the present study, considering the individual fibres might be useful. A model of the ligament fibres, both of the interosseous ligaments and of the ligaments already considered in the present study, can be developed based on measured or estimated ligament-fibre insertion-sites and known displacements of these insertion sites relative to each other. With another model containing the modeled sophisticated ligament behaviour, the bone geometry, a simplified model of the wrist joint (a fixed distal row, three adjustable proximal carpals and a radius) and an external reaction force the bone-contact forces between the structures of this simplified model might be estimated based on inverse dynamics calculations. When these forces are studied in relation to the morphology of the carpals and the ligaments and as a function of applied changes of the morphology, the morphology will be explained.

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SAMENVATTING: KINEMATICA EN LIGAMENTGEDRAG VAN HET POLSGEWRICHT

INLEIDING

Het polsgewricht vormt de geleding tussen de onderarm en de hand. Door middel van dit gewricht is het mogelijk de hand in twee loodrecht op elkaar staande vlakken, in flexie- en deviatie-richting te bewegen ten opzichte van de onderarm. Anatomisch bekeken wordt het polsgewricht gevormd door de distale gewrichtsvlakken van de botten van de onderarm, de radius (het spaakbeen) en de ulna (de ellepijp), door de acht carpale botstukjes, door de proximale gewrichtsvlakken van de metacarpalia (de middenhandsbeentjes), en door een groot aantal collagene structuren (ligamenten en de ulnaire gewrichtsdiscus). De geometrie van deze structuren, hun materiaaleigenschappen en hun onderlinge posities bepalen het functioneren van het polsgewricht. Inzicht in deze morfologische grootheden (vormen, materiaalkarakteristieken en onderlinge verhoudingen) is dan ook noodzakelijk om het mechanisme van het polsgewricht te begrijpen. Inzicht hebben in morfologische grootheden betekent dat deze eigenschappen begrepen kunnen worden als afhankelijke van de functie van het gewricht. Toegepast op een onderdeel van het bewegingsapparaat, zoals het polsgewricht, betekent dat dat de vormeigenschappen verklaard moeten worden in het licht van de functie van het bewegingsapparaat, namelijk bewegen. Bewegingen kunnen uitsluitend veroorzaakt worden door krachten. Om dus van nut te kunnen zijn voor het bewegingsapparaat moeten de onderdelen van dit systeem krachten kunnen genereren of doorleiden. Voor het begrijpen van de vormeigenschappen van de onderdelen van het bewegingsapparaat in het algemeen en van het polsgewricht in het bijzonder is het daarom nodig ze te beoordelen in het licht van hun mogelijkheid om krachten te genereren of door te leiden.

Het polsgewricht bevat alleen structuren die krachten kunnen doorleiden; spieren, de krachtgeneratoren van het bewegingsapparaat hechten niet direct aan in het polsgewricht. Krachtdoorleiding kan plaatsvinden door contact tussen botdelen en door vervorming van collagene structuren. In deze studie is de aandacht gericht op het krachtdoorleidende vermogen van ligamenten. Concreet betekent dat, dat de vraag beantwoord moet worden, hoe groot zijn de krachten die in ligamenten ontstaan als ze gerekt worden, en wat is de betekenis van deze krachten voor het mechanisme van het polsgewricht. In de hoofdstukken 2, 3, 4 en 5 is deze vraag uitgewerkt. In hoofdstuk 2 is gekeken hoe en hoeveel de lengte van ligamenten verandert tijdens flexie- en deviatie-bewegingen van de hand. De materiaaleigenschappen van de ligamenten van het polsgewricht worden in hoofdstuk 3 behandeld. In hoofdstuk 4 wordt een methode behandeld, om ligamentlengteverandering en materiaaleigenschappen aan elkaar te relateren, zodat ligamentkrachten geschat kunnen worden. Hoofdstuk 5 tenslotte geeft deze krachten voor een aantal ligamenten tijdens flexie en deviatie van de hand.

Bij de bestudering van het polsgewricht is het tot nu toe gebruikelijk geweest, enkel fenomenen die samengaan met flexie en deviatie van de hand te bestuderen. Echter, ook combinaties van deze bewegingen zijn mogelijk. Dit zijn met name de bewegingen die tijdens het normale gebruik van het polsgewricht uitgevoerd worden. In het licht van dit laatste gegeven is het niet waarschijnlijk dat bestudering van enkel flexie en deviatie van het polsgewricht leidt tot volledig inzicht in de vorm-functie relatie van het polsgewricht. De beschrijving van het functie-aspect van deze relatie zou namelijk wel eens niet afdoende kunnen zijn. Het onderzoek van de beweging van de carpalia en lengteveranderingen van ligamenten bij combinaties van flexie- en deviatiebewegingen is het onderwerp van studie in hoofdstuk 6.

SAMENVATTING VAN DE HOOFDSTUKKEN 2 TOT EN MET 6

Hoofdstuk 2: Verlenging van ligamenten van het polsgewricht en 3-dimensionale bewegingen van carpale beenstukjes

De bewegingen van de carpalia en lengteveranderingen van een zestal ligamenten van het polsgewricht tijdens flexie en deviatie van de hand zijn vastgelegd. Daarvoor is gebruik gemaakt van Röntgenstereofotogrammetrie. Door middel van Röntgenstereofotogrammetrie is het mogelijk de 3-dimensionale positie van karakteristieke punten van het bewegingsapparaat, *i.c.* het polsgewricht, te bepalen. Als karakteristieke punten werden radio-opake markeringen, kleine tantalum bolletjes (Ø: 0.5, 0.8 of 1.0 mm), in de carpale beenstukjes en op de ligamenten aangebracht. Op deze manier was het mogelijk de botstukjes als 'starre lichamen' te modelleren en hun bewegingen te meten. In de ligamenten werden de markeringen in een rij langs een ligamentvezel gelegd, en representeerde de som van de afstanden tussen opeenvolgende markeringen de lengte van het ligament.

De resultaten van dit onderzoek bleken op belangrijke punten te verschillen van lengteveranderingen die voorspeld werden door gangbare concepten met betrekking tot het mechanisme van het polsgewricht. De oorzaak van dit verschil ligt in het feit dat in die concepten uitgegaan wordt van 2-dimensionale bewegingen van carpalia rond een vaste bewegingsas. Dit onderzoek, evenals vergelijkbare studies, waarin het 3-dimensionale aspect van het gewricht bekeken werd, laat zien dat de bewegingen buiten het vlak van de handbeweging allerminst verwaarloosbaar zijn. Juist ten gevolge van de bewegingen van carpalia in de richting buiten het hoofdvlak van de handbeweging blijken sommige ligamenten veel te verlengen. Ook kan het verschil tussen de resultaten van dit onderzoek en eerdere voorspellingen toegeschreven worden aan het feit dat ligamenten in bepaalde situaties gedwongen worden rond een hoekje te lopen, doordat een tussenliggend botstukje in een tweede vlak beweegt.

Globaal kan gesteld worden dat de palmaire ligamenten tussen de radius en het lunatum en het capitatum verlengen bij dorsaal flexie en ulnair deviatie van de hand. De palmaire vezels tussen lunatum en triquetrum vertonen tijdens geen enkele beweging enige lengteverandering. Het dorsale ligament tussen radius en triquetrum wordt langer bij palmaire flexie van de hand. Verder werd het duidelijk dat verschillende vezels in een ligament niet evenveel verlengen of verkorten.

Hoofdstuk 3: De stijfheid van ligamenten van het polsgewricht

Door middel van trekbank-testen werd de stijfheid van de ligamenten van het polsgewricht bepaald. Daartoe werden van deze ligamenten bot-ligament-bot preparaten gemaakt. De tangent modulus van deze ligamenten werd bepaald, als een maat voor de stijfheid van het materiaal waaruit een ligament bestaat.

Het bleek dat de meeste ligamenten bestaan uit materiaal dat qua stijfheid niet significant van elkaar verschilt. Slechts twee ligamenten bleken hierop een uitzondering te vormen en uit stijver materiaal te bestaan. Voor het palmaire ligament tussen de radius en het capitatum en het dorsale tussen de radius en het triquetrum werden tangent moduli vastgesteld van respectievelijk 83 en 93 MPa. De overige ligamenten hadden waarden variërend tussen 25 en 50 MPa. Een verklaring voor deze verschillen is niet gevonden.

***Hoofdstuk 4:* Een methode om indirect ligamentkrachten te schatten, het effect van preconditioneren op de schattingsresultaten**

In kleine ligamenten, zoals die voorkomen in het polsgewricht is het niet mogelijk om op directe wijze, bijvoorbeeld door middel van 'buckle transducers', kracht te meten. Daarom is hiertoe een indirecte techniek ontwikkeld, die gebaseerd is op de wetenschap dat de kracht die een ligament doorleidt afhankelijk is van de materiaalkarakteristieken en van de hoeveelheid rek, die in het betreffende ligament optreedt. Tijdens bewegingen *in vitro* worden de lengteveranderingen van ligamenten bepaald door middel van Röntgenstereofotogrammetrie (hoofdstuk 2). Vervolgens worden bot-ligament-bot preparaten gemaakt, aan de hand waarvan in de trekbank, eveneens door middel van Röntgenstereofotogrammetrie, de lengte bepaald wordt wanneer het ligament nog net onbelast is. Deze lengte wordt beschouwd als de nullengte. Vervolgens wordt, ook in de trekbank, de relatie tussen ligamentlengte en ligamentkracht vastgelegd (hoofdstuk 3). Combinatie van deze drie gegevens, *in vitro* ligament lengteverandering, nullengte en lengte-kracht relatie, leidt tot ligament-krachtschattingen voor *in vitro* bewegingen.

De nauwkeurigheid van de methode blijkt goed te zijn. Schatting van de meetfouten aan de hand van bekende nauwkeurigheden van de verschillende metingen waaruit de methode bestaat, laten zien dat de fouten klein zijn in verhouding tot de geschatte krachten. Het al dan niet preconditioneren van de ligamenten voordat de lengte-kracht relatie bepaald wordt, blijkt grote invloed te hebben op de uiteindelijke geschatte krachten.

Hoofdstuk 5:* In vitro *rekken en krachten in ligamenten van het polsgewricht bij flexie- en deviatiebewegingen van de hand

De methode beschreven in hoofdstuk 4 is toegepast op de ligamenten van een zevental polsgewricht-preparaten om de krachten tijdens *in vitro* flexie- en deviatiebewegingen van de hand ten opzichte van de onderarm te bepalen. Tegelijkertijd zijn ook de bewegingen van de carpalia tijdens deze bewegingen vastgelegd door middel van Röntgenstereofotogrammetrie. In tegenstelling tot de bewegingspatronen van de carpalia laten de krachtpatronen van de ligamenten een grote variatie zien tussen de verschillende polsgewricht-preparaten. Deze variatie betreft de kwantitatieve aspecten van de patronen, kwalitatief zijn de patronen voor overeenkomstige ligamenten uit verschillende specimens gelijk. De variatie in de krachtpatronen blijkt te kunnen worden teruggevonden in variaties in de nullengte van de ligamenten en in variaties in de kracht-rek relaties van de ligamenten tussen de specimens. Het lijkt onwaarschijnlijk dat deze verschillen volledig door interindividuele variaties verklaard kunnen worden. Een deel van de variatie lijkt in ieder geval aan artefacten in de methode toegeschreven te moeten worden, met name effecten van het ingevroren bewaren van de polsgewricht-preparaten en van het ongewenst preconditioneren zouden de variatie negatief hebben kunnen beïnvloeden.

Uit het feit dat de variatie in de bewegingspatronen door deze artefacten niet toegenomen blijkt te zijn, lijkt de conclusie dat de ligamenten geen grote rol spelen bij het controleren van de bewegingen van de carpalia tijdens normale handbewegingen aannemelijk te zijn.

Hoofdstuk 6: Bewegingen van carpale beenstukken en ligamentverlengingen bij handbewegingen, die de hele bewegingsruimte van de hand beslaan

Door middel van Röntgenstereofotogrammetrie zijn de bewegingen van de carpalia en de lengteveranderingen van de ligamenten in het polsgewricht vastgelegd bij bewegingen in de volledige bewegingsruimte van het polsgewricht. In tegenstelling tot in eerdere studies zijn in dit onderzoek niet alleen de flexie- en de deviatiebeweging van de hand bestudeerd, maar is ook gekeken naar de fenomenen die gepaard gaan met bewegingen in richtingen die combinaties van flexie en deviatie zijn.

Het blijkt dat tijdens deze bewegingen het capitatum en het trapezium, twee van de carpalia van de distale rij, nauwgezet de bewegingen van de hand volgen. Daarentegen blijken de bewegingen van het lunatum en het scaphoïdeum, carpalia van de proximale rij, niet direct beïnvloed te worden door de bewegingen van de hand. Deze carpalia lieten bij bijna alle handbewegingen duidelijke bewegingen in andere richtingen dan in die van het vlak van de handbeweging zien. Voorst bleek uit de bewegingspatronen van de carpalia, dat flexie en deviatie slechts exemplaren van mogelijke handbewegingen zijn, en dat zij als zodanig niet representatief zijn voor de bewegingsmogelijkheden, *c.q.* de functie van het polsgewricht.

De maximale lengteveranderingen van de ligamenten tijdens de bewegingen, die in deze experimenten opgelegd werden, blijken niet groter te zijn dan die, die waargenomen werden tijdens flexie en deviatie van de hand.

SLOTBESCHOUWINGEN

Uit de resultaten van deze studie worden tenslotte een aantal conclusies getrokken voor zowel de medische praktijk als de theorievorming met betrekking tot het polsgewricht.

In de medische praktijk is het toepassen van gedeeltelijke arthrodesen van het polsgewricht een gebruikelijke therapie bij ernstige instabiliteiten. Een dergelijke arthrodese gaat altijd gepaard met een verlies aan bewegelijkheid van de hand ten opzichte van de onderarm. Op basis van de gegevens van hoofdstuk 6, wordt geconcludeerd dat met het oog op het tegengaan van dit bewegingsverlies het beter zou zijn carpalia uit dezelfde rij met elkaar te verbinden (proximaal of distaal), dan carpalia uit verschillende rijen.

Aan de hand van de resultaten van hoofdstuk 2 wordt geconcludeerd dat de verlenging van een ligamentvezel niet alleen afhankelijk is van de bewegingen van de carpalia, die door de vezel verbonden worden, maar dat ook de relatieve positie van de vezel ten opzichte van die carpalia van belang is. Hieruit kan afgeleid worden dat elke vezel in een ligament anders zal verlengen. De conclusie van deze analyse is dat voor een adequate beschrijving van het gedrag van de relatief brede ligamenten van het polsgewricht, een meer verfijnd model nodig is, dat het gedrag van vezels of van groepen van vezels beschrijft.

Met betrekking tot de rol van ligamenten in het mechanisme van het polsgewricht, wordt geconcludeerd dat het erg onwaarschijnlijk is dat ligamenten bijdragen aan het positioneren van de carpalia bij verplaatsingen van de hand binnen het normale bewegingsbereik. Deze rol zal waarschijnlijk toegedacht moeten worden aan de botcontactkrachten die tussen de carpalia optreden. De ligamentkrachten lijken van belang te zijn bij het instandhouden van de integriteit van het gewricht als de uiterste standen bereikt worden. In deze situaties nemen de krachten die door de ligamenten worden doorgeleid sterk toe.

Met betrekking tot het functioneren van het polsgewricht zijn in de literatuur een tweetal concepten geopperd. Ten eerste is er het 'horizontale rijen' concept, waarbij het polsgewricht ingedeeld wordt in een proximale en een distale rij van carpalia. Deze rijen worden geacht bij bewegingen van de hand rond een vaste rotatie-as te bewegen. Hierbij worden de bewegingen binnen een rij verondersteld miniem te zijn, en de bewegingen tussen de rijen tegengesteld. Het tweede concept is dat van de 'verticale kolommen', hierbij worden de carpalia en radius en ulna in drie kolommen in gedeeld die elk een aparte functie toebedacht krijgen. De proximale carpalia fungeren in dit concept als schakels tussen de kolommen. De gegevens die in dit onderzoek verzameld zijn, en met name de resultaten van hoofdstuk 6 lijken geen van beide concepten te ondersteunen. Eerder lijkt daarentegen een model van het polsgewricht dat dit systeem beschrijft als bestaand uit 3 segmenten, *i.c.* de radius, de proximale rij van carpalia, en de hand inclusief de distale rij van carpale beenstukjes bij de werkelijkheid aan te sluiten. Twee van deze segmenten, de radius en de hand, kunnen als starre lichamen beschouwd worden, het derde, de rij van proximale carpalia, is vervormbaar. De deformatie van deze rij wordt bepaald door krachten die doorgeleid worden via ligamenten en gewrichtsvlakken. De richting en grootte van deze krachten worden bepaald door de morfologie van het gewricht.

DANKWOORD

Dat sommige woorden clichés zijn, wil niet zeggen dat ze minder waar of minder oprecht zijn. Dat geldt zeker ook voor de stellingen dat onderzoek *teamwork* is en een promotie-onderzoek als solo-karwei onbegonnen werk is. Ook dit proefschrift was niet het werk van een eenling. Vanaf deze plek wil ik mijn teamgenoten danken voor hun inzet; enigen van hen wil ik hier apart noemen.

Als eerste wil ik Jan Kooloos noemen. Jan, je hebt je in de afgelopen 4 jaar een begeleider getoond, om wie menig promovendus mij zou kunnen benijden. Niet alleen heb ik van en via jou geleerd wat functionele morfologie kan zijn, maar ook sloot jouw vermogen tot ordenen perfect aan bij mijn neiging zaken chaotisch te structureren. Veel belangrijker nog voor een beginneling is, dat er iemand is waar hij zijn frustraties en boosheid kwijt kan, en waar hij zijn wildste ideeën kan toetsen. Daarnaast zijn ook de 'De Koninckjes' die we op de Antwerpse Groenplaats genoten, de 'Dos Equis' in San Diego en de donderdagavondbijeenkomsten goede herinneringen.

Uiteraard ben ik dank verschuldigd aan mijn beide promotores, Rik Huiskes en John Kauer. John, ik denk dat jij de meeste slapeloze nachten, in ieder geval in figuurlijke zin, aan dit project hebt overgehouden. Het was duidelijk ook jouw promotie-onderzoek. Je hebt dan ook steeds de mogelijkheden en ruimte geschapen, die tot een goed resultaat leidden. Rik, ondanks je volle agenda, die een spontane wandeling van mij naar de 'overkant' tot een riskante onderneming maakte, zag je toch kans op de juiste momenten stimulerend op te treden. Dat deed je ook tijdens de jongste E.S.B.-bijeenkomst in Århus, waar je het mede-voorzitterschap van een parallel-sessie liet voor wat het was om mijn voordracht bij te wonen. Je betrokkenheid bleek ook uit de wijze waarop je mijn manuscripten beoordeelde. In eerste instantie was zo'n rood ingekleurd manuscript schrikken, later begreep ik dat dat het gevolg van je perfectionisme was. Ik geloof dat ik daar veel van geleerd heb.

Ook onmisbaar bij de uitvoering van dit project was Willem van de Wijdeven. Op elk moment van de dag kon ik hem tijdens zijn werkzaamheden storen om een probleem dat zich tijdens mijn experimenten voordeed op te lossen. Dergelijke problemen werden dan binnen de kortste keren naar een andere wereld geholpen. Willem, al die trekbank- en RSA-experimenten waren zonder jouw technisch inzicht vast niet zo soepel verlopen, het was

een genoegen om daarop te kunnen vertrouwen.

Ton de Lange was de startmotor van mijn Nijmeegse periode. Hoe belangrijk iemand is, die je de weg wijst in een nieuwe omgeving met nieuwe technieken en onbekende programmatuur, blijkt later pas, wanneer je alles voor de eerste keer zelf moet doen. Ton, je aanjaag-activiteiten bleken uit te monden in vriendschap, buurtgenootschap en gezamenlijk congresbezoek; ik hoop dat dit nog lang zal voortduren.

Het schrijven van computerprogramma's voor dit project heeft Huub Peeters voornamelijk voor zijn rekening genomen. Daarnaast was Huub ook degene die onze interdepartementale voetbalpartijen organiseerde, en zo bijdroeg aan de broodnodige ontspanning.

Leendert Blankevoort behoort tot de categorie twijfelgevallen: Leendert, je was zowel begeleider als lotgenoot! Als begeleider stond je vaak klaar om assenstelsels de juiste oriëntatie te geven en andere gelijksoortige, kinematische fenomenen de juiste draai. Maar ook de raad die je gaf als collega-promovendus was vaak een wijze.

Functioneel morfologisch en biomechanisch onderzoek kan niet uitgevoerd worden zonder 'bio', zonder vormen, in dit geval preparaten van het polsgewricht. Het 'verzamelen', bewerken en bewaren hiervan, werd verricht door de amanuenses van de vakgroep Anatomie en Embryologie: Cor Cornelissen, Sjaak de Haardt en Hans Remers.

Ook dr. Lemmens van de afdeling Radiodiagnostiek en de vele laboranten die ik daar voor de voeten liep, ben ik dankbaar voor de gelegenheid die zij mij boden om honderden röntgenfoto's te ontwikkelen.

Een deel van het meetwerk van dit onderzoek is uitgevoerd door studenten Gezondheidswetenschappen en Geneeskunde die bij de werkgroep FABA stage liepen: Michel Dings, Hans Otten, Paul Schwering en Marc Vorstenbosch. Met name Hans Otten, die, al rokend en meedrummend met de muziek uit zijn *walkman*, veel vrije tijd stopte in het meetwerk van hoofdstuk 6, ben ik meer dan een vermelding op deze plaats verschuldigd.

Ik weet niet of geluk komt aanwaaien, of dat je het moet afdwingen. In ieder geval heb ik een belangrijk deel van de gelukkige toestand waarin ik mij bevind, aan mijn ouders te danken, die de omstandigheden schiepen waarin ik mijn vleugels kon uitslaan, en belangrijker nog, mij voortdurend stimuleerden om ze ook daadwerkelijk uit te spreiden.

Last, but certainly not least, was er nog iemand met een opgeheven duimpje, dat mij aanmoedigde om toch maar weer eens te lachen als het allemaal even teveel was geworden. Zij zorgde dat mijn handen vrijbleven voor dit 'belangrijke' werk.

CURRICULUM VITAE

Op 28 februari 1962 ben ik in Heerlen geboren. In 1980 behaalde ik het gymnasium-β diploma aan het St.Janscollege in Hoensbroek. Daarvoor heb ik een groot deel van mijn leven op kleuter- en basisschool doorgebracht. Buiten die schooluren vulde ik de eerste helft van mijn leven tot nu toe voornamelijk met lichamelijke activiteiten (voetballen, zwemmen, tennissen, fietsen en schaatsen), het volpennen van schoolkranten en het discussiëren over politiek.

In september 1980 begon ik met de studie Lichamelijke Opvoeding (tegenwoordig Bewegingswetenschappen) aan de Vrije Universiteit in Amsterdam. Nadat ik in twee jaar mijn kandidaatsexamen had afgelegd, kreeg in 1982 studeren een ruimere betekenis voor mij: dat hield niet alleen in dat ik ging roeien, maar ook dat studeren niet langer tentamens leren was, maar meer en meer veranderde in het verkrijgen van inzicht en het leren stellen van de juiste vragen. Vooral voor vragen m.b.t. coördinatie van bewegen ging ik een bijzondere interesse ontwikkelen. Dit leidde tot een keuze voor twee hoofdvakken (Functionele Anatomie en Psychologie m.b.t. Lichamelijke Opvoeding), een stage in een onderzoeksproject naar de interactie tussen waarnemen en handelen bij tafeltennis, en een afstudeerscriptie over de coördinatie van het gaan van de mens.

Vlak voordat ik afstudeerde begon ik in december 1986 aan een AiO-schap bij de vakgroep Anatomie en Embryologie van de Katholieke Universiteit Nijmegen. In dit AiO-project, dat uitgevoerd werd in samenwerking met de sectie Biomechanica van het instituut voor Orthopaedie van het Academisch Ziekenhuis Nijmegen, heb ik me bezig gehouden met de betekenis van ligamenten voor het mechanisme van het humane polsgewricht. Dit onderzoek leidde tot dit proefschrift. Behalve voor het produceren van een proefschrift kon ik in Nijmegen gelukkig ook nog tijd vinden om te fotograferen, te schaatsen en mee te helpen een schaatsvereniging op te richten.

Sinds 1 augustus 1991 werk ik als toegevoegd onderzoeker bij de vakgroepen Functionele Morfologie en Algemene Heelkunde en Heelkunde van Grote Huisdieren van de Rijksuniversiteit Utrecht. In deze functie hoop ik me weer meer met vragen rond de coördinatie van het bewegen (van paarden) bezig te kunnen gaan houden.

STELLINGEN
behorende bij het proefschrift
WRIST JOINT KINEMATICS AND LIGAMENT BEHAVIOUR

1- De indeling in intrinsieke en extrinsieke ligamenten in het polsgewricht (*J. Taleisnik*, J.Hand Surgery, *1, 1976*) wordt niet gestaafd door functionele argumenten.

2- Een ligament van het polsgewricht dient niet als één lijnelement gemodelleerd te worden.
Dit proefschrift.

3- Om verlengingspatronen van ligamenten van het polsgewricht te kunnen begrijpen is inzicht in de 3-dimensionale bewegingen van de beenstukken in dit gewricht essentieel.
Dit proefschrift.

4- Met het oog op modelvorming van het polsgewricht is het geoorloofd de bewegingen tussen de distale carpalia onderling te negeren. Hetzelfde geldt voor de bewegingen tussen de distale carpalia en de metacarpalia, met uitzondering van metacarpale I.
Dit proefschrift.

5- De vorm van de gewrichtsvlakken van de carpalia en van de radius bepaalt in hoge mate de bewegingen van deze botstukken ten opzichte van elkaar, de ligamenten spelen hierbij een ondergeschikte rol.
Dit proefschrift

6- De rol die ligamenten spelen in het mechanisme van het polsgewricht van de mens verschilt wezenlijk van die van ligamenten in het kniegewricht.
Dit proefschrift

7- De functionele anatomie zoals die onderwezen wordt in de meeste studieboeken levert onvoldoende inzicht voor het begrijpen van spierfuncties. Doordat zij zich vooral op de morfologische aspecten van het bewegingsapparaat richt, en maar in geringe mate rekening houdt met de context waarin bewogen wordt, blijft het krachtenspel dat aan bewegingen ten grondslag ligt buiten beschouwing.

8- Er dient geregeld te worden dat Nederland ontregeld wordt.

9- Democratie moet een redelijke, niet door gevestigde belangen beheerste botsing van meningen zijn. *(uit: Politiek voor de post-materialistische generatie, F. Jensma,* NRC Handelsblad, *28 september 1991).*

10- Het is een uiting van hypocrisie wanneer regeringen die hun beleid voornamelijk op economische gronden baseren, een onderscheid maken tussen politieke en economische vluchtelingen.

11- Evenals vroegere goden zullen ook de godinnen Technologische Vooruitgang en Productiviteit een illusie blijken te zijn. (*geïnspireerd door Net als zij, E. Galeano,* De Volkskrant, *5 oktober 1991*)

12- Het feit dat de spiercoördinatie van de schaatsbeweging niet overeenkomt met die van het gaan mag geen reden zijn schaatsen als een onnatuurlijke beweging te karakteriseren.

13- Het verbieden van doping ter verbetering van sportprestaties kan niet met redelijke argumenten onderbouwd worden.

14- Wie altijd met twee benen op de grond blijft zal nooit eens een ander perspectief van de werkelijkheid ervaren.

15- Het moet niet uitgesloten worden dat de resultaten van fysiotherapeutische effectonderzoeken meer zeggen over ons inzicht in biologische systemen, dan over het therapeutische effect.

16- Geloof in Murphy's Law is niet verenigbaar met het vertrouwen dat dit proefschrift op betrouwbare gegevens berust.

Hans H.C.M. Savelberg Rosmalen, November 1991